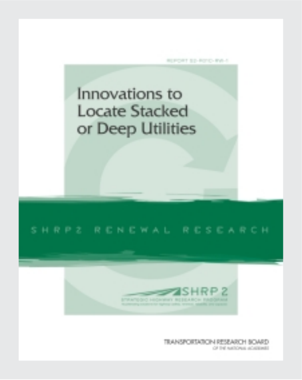

Innovations to Locate Stacked or Deep Utilities

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The Second

STRATEGIC HIGHWAY RESEARCH PROGRAM

SHRP 2 REPORT S2-R01C-RW-1

Innovations to Locate Stacked or Deep Utilities

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TRANSPORTATION RESEARCH BOARD
WASHINGTON, D.C.
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Subject Areas

Construction
Highways

The Second Strategic Highway Research Program

America's highway system is critical to meeting the mobility and economic needs of local communities, regions, and the nation. Developments in research and technology—such as advanced materials, communications technology, new data collection technologies, and human factors science—offer a new opportunity to improve the safety and reliability of this important national resource. Breakthrough resolution of significant transportation problems, however, requires concentrated resources over a short time frame. Reflecting this need, the second Strategic Highway Research Program (SHRP 2) has an intense, large-scale focus, integrates multiple fields of research and technology, and is fundamentally different from the broad, mission-oriented, discipline-based research programs that have been the mainstay of the highway research industry for half a century.

The need for SHRP 2 was identified in *TRB Special Report 260: Strategic Highway Research: Saving Lives, Reducing Congestion, Improving Quality of Life,* published in 2001 and based on a study sponsored by Congress through the Transportation Equity Act for the 21st Century (TEA-21). SHRP 2, modeled after the first Strategic Highway Research Program, is a focused, time-constrained, management-driven program designed to complement existing highway research programs. SHRP 2 focuses on applied research in four areas: Safety, to prevent or reduce the severity of highway crashes by understanding driver behavior; Renewal, to address the aging infrastructure through rapid design and construction methods that cause minimal disruptions and produce lasting facilities; Reliability, to reduce congestion through incident reduction, management, response, and mitigation; and Capacity, to integrate mobility, economic, environmental, and community needs in the planning and designing of new transportation capacity.

SHRP 2 was authorized in August 2005 as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). The program is managed by the Transportation Research Board (TRB) on behalf of the National Research Council (NRC). SHRP 2 is conducted under a memorandum of understanding among the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and the National Academy of Sciences, parent organization of TRB and NRC. The program provides for competitive, merit-based selection of research contractors; independent research project oversight; and dissemination of research results.

SHRP 2 Report S2-R01C-RW-1

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SHRP 2 STAFF

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This work was sponsored by the Federal Highway Administration in cooperation with the American Association of State Highway and Transportation Officials. It was conducted in the second Strategic Highway Research Program (SHRP 2), which is administered by the Transportation Research Board of the National Academies. The project was managed by Charles Taylor, Special Consultant for SHRP 2 Renewal; James Bryant, Senior Program Officer for SHRP 2 Renewal; and Andy Horosko, Special Consultant for SHRP 2 Renewal. Ralph Hessian, Special Consultant for SHRP 2 Renewal, also contributed to this report.

The research reported on herein was performed by the Gas Technology Institute (GTI), Underground Imaging Technologies (UIT), and Visible Assets Incorporated (VAI). End-user outreach and general guidance was provided by J. H. Anspach Consulting.

FOREWORD

Andy Horosko and Ralph Hessian, *SHRP 2 Special Consultants, Renewal*

This report documents research and development efforts to improve technologies for detecting, identifying, and mapping deeply buried utilities and utilities that are difficult to locate because of stacking in utility-congested areas. Five promising geophysical and mapping technologies were identified for review. For two of them—long-range RFID tags and active acoustic locating devices—prototypes were developed and field-tested. The prototype RFID tags showed some promise for development into a utility product. The active acoustic locating technology, however, did not perform well. This report will be of interest to engineers and businesses investigating the performance of technologies to improve the locatable zone for deeply buried or stacked utilities.

Underground utility installations are common within highway rights-of-way. The location and specific characteristics of many buried utility lines have not been properly documented and thus present a challenge for highway renewal projects. The discovery of unexpected utility lines during a project can pose considerable risk to workers' safety and disrupt the project's schedule. Highway renewal projects depend on the availability of accurate buried-utility records and information to support effective planning, design, and delivery of renewal work.

Varying site soil, geology, and environmental conditions require a suite of innovative nondestructive technologies and methods and a decision-support framework to provide the necessary underground utility information for renewal projects. SHRP 2 Renewal Project R01, Encouraging Innovation in Locating and Characterizing Underground Utilities, provided the basis for a series of research and development projects that seek to provide the products to serve this highway renewal business need.

This report presents research into extending the locatable zone for deeply buried and stacked utilities. The project started with a literature search to identify possible technologies for detecting and mapping utilities. These technologies were further screened to define promising near-term solutions. Five were identified for further research and development.

Key performance indicators were developed to guide the initial prototype development and associated testing. After detailed review and in some cases initial prototype development, long-range RFID tags and active acoustic locating devices were selected to proceed to final prototype development and testing. Prototypes of these two types of technologies were constructed and tested in real-world conditions. The general finding was that both technologies require more development to bring them to a commercial-ready state. The RFID technology was judged to be closer to commercial readiness, but it requires further packaging and ergonomic improvements for field use.

This project worked closely with the SHRP 2 R01B project, Utility Locating Technology Development Using Multisensor Platforms, to avoid duplication and provide a complementary set of tools. Some activities of the two projects were conducted together and jointly analyzed.

CONTENTS

Executive Summary

One of the recommendations from the SHRP 2 R01 study, Encouraging Innovation in Locating and Characterizing Underground Utilities, was "the development of locating technologies that target deep utilities that currently cannot be detected by surface-based approaches. These could include direct-path detection methods deployed from inside a utility or cross-bore techniques based on vacuum-excavated boreholes." This recommendation garnered a low priority because of its expected technological difficulty and probable low return on investment. As a result, there was a slight realignment in goals to include the concept that it is not always deep utilities that prove difficult to locate; there are also utility systems that are hidden or masked by those utilities that reside on top of them. It is more likely that these shallower utilities, difficult to locate, would be more frequently impacted by highway construction. Therefore, the SHRP 2 R01C project proceeded with the concept that "innovations to improve the extent of the locatable zone" might produce a larger return on investment to the transportation community.

The R01C project worked closely with the R01B project, Utility Locating Technology Development Using Multisensor Platforms, to avoid duplication and provide a complementary set of tools. Some activities of the two projects were conducted together and jointly analyzed in order to be in harmony. Additionally, the two projects had a common technical expert task group (TETG) and user group for guidance and feedback on direction. One of the first activities undertaken by the projects was a literature search.

Literature Search

The literature search discovered 24 possible technologies available to detect and map utilities. Some of these techniques require a large amount of development to make them usable for application in the field. The goal of this R01C project is development of near-term solutions. Therefore, techniques requiring technological breakthroughs were eliminated from consideration, as were technologies that are unsuitable for deep or stacked utilities. Factors that make them unsuitable include Federal Communications Commission (FCC) power and frequency restrictions, geometry restrictions, and terrain/environmental issues such as traffic.

On the basis of the literature review and with guidance from the TETG and the user group, this project proposed research into developing five complementary technologies:

1. Pipe mapping using inserted inertial navigation devices;
2. A scanning electromagnetic (EM) locator;
3. Seismic reflection location using an aboveground seismic generator;
4. Active acoustic location using an acoustic generator coupled to the pipe being located; and
5. Long-range (in excess of 10 ft) radio frequency identification (RFID) tags.

Details on all five technologies and their progress are included in this report. During the course of the project, these five technologies were reduced to two for prototype development:

- Smart tags detectable on utilities at depths of 20 ft. These can be read to obtain stored information such as pipe depth, date of installation, pipe size, and content.
- Active acoustic technology that injects pulses of sound into a pipe utility. The sound propagates though the medium in the pipe and is detected at the ground surface. This technology uses lower frequencies than units on the market and uses time of flight (TOF) rather than amplitude detection. The same equipment can be used in a passive mode to detect certain utilities that cause vibrations, such as three-phase electric cables.

Smart Tag (RFID) Development

RFID technology is a wireless technology that can provide both location and positive identification. A typical RFID system includes two components: a transceiver (equipped with an antenna) and a buried RFID tag that is programmed with unique information. The transceiver initiates the communication with the buried RFID tag. Commercial RFID readers typically incorporate the transceiver and the antenna into the same assembly. Commercial smart tags now in place can be detected in soils to a maximum of 6 ft. This limitation forces the placement of tags over, rather than directly on, facilities beyond this depth. Nearby excavation may destroy or relocate these “floating” tags. To overcome the depth limitation, it was necessary to develop active tags containing an internal battery. Long battery life and range are therefore the two critical components not yet found in commercial RFID systems. The smart RFID tag developed from this research project is suitable for utilities at 20-ft depths, with an expected 50-year battery life.

Active Acoustic Development

This prototype tool builds on an existing device designed for the gas industry. It consists of a transmitter for acoustic signals and six receiving accelerometers. In application, the acoustic transmitter is coupled directly to a free end of the pipe being located. The array of six wireless sensors is deployed across the suspected path of the pipe. An acoustic signal is sent, and the signals from the sensors are correlated. The user receives feedback on where the signal strength is greatest. The user can move the sensors until the best signal is obtained and centered. The depth can then be estimated from the acoustic TOF.

Conclusions

The solutions to locating deep and stacked utilities are not easy to come by with geophysics. Government policies, utility installation practices, geotechnical constraints, and physics all work against developing cost-effective and field-implementable solutions. Mandating accurate and reproducible records of utilities during installation is the recommended path forward to keep the problem from getting worse. Mandating placement of some type of RFID for every instance where a utility is exposed is a reasonable means to implement this recommendation. The R01C project tested two prototype tools that with further development may combine to provide solutions in certain situations. The project has also developed valuable information for future researchers on three technologies that did not reach the prototype stage.

CHAPTER 1

Background

The original objective of the SHRP 2 R01C project was to improve the location accuracy of buried utilities at depths below 10 ft. A separate project, R01B, dealt with multisensor platforms for shallower depths. The primary driver of the project and venue for technology demonstration is highway construction. Department of transportation (DOT) projects, by their nature, involve all utilities within the actual or proposed public right-of-way (ROW) and many times for some distance beyond for relocation design purposes.

In order to improve the detection and reliable [ASCE 38-02 Quality Level B (QL-B)] determination of the positions of buried utilities within an expanded locatable zone, a project team with diverse and unique qualifications was assembled. In recognition that each location has its own challenges, the approach was multifaceted. The original project team consisted of the following organizations:

- Gas Technology Institute (GTI);
- Underground Imaging Technologies (UIT);
- Visible Assets Incorporated (VAI);
- Geospatial Corporation;
- J. H. Anspach Consulting; and
- Water and Sewer Innovation Research (WASIR) Consultants.

The project objectives were modified based on the Phase 1 findings to accurately locating a wide range of facilities embedded in a challenging environment. Some specific goals were to be able to locate deep facilities and also facilities that may be stacked in such a fashion that there are interferences.

The project team has expertise in the following areas:

- Seismic and acoustic technologies for use in soils.
- Electromagnetic (EM) technologies for the locating of metallic piping and features.
- Smart-tagging technologies for marking and identifying buried assets.
- Expertise in the standards and practices of the following industries:
  - ○ Highway construction;
  - ○ Gas transmission and distribution; and
  - ○ Oil and gas exploration.

To achieve ASCE 38-02 QL-B, part of the process involves the application of appropriate surface geophysical methods to attempt to determine the existence and horizontal position of all utilities within scope within the project limits. This utility geophysical search activity is called “designating.” The utility information obtained in this manner is surveyed to project control. Designating provides data that can solve problems caused by inaccurate utility records, abandoned or unrecorded facilities, and lost references. QL-B information provides reliable information to reduce the project risks during project development. Decisions regarding location of storm drainage systems, footers, foundations, and other design features can be made to successfully avoid conflicts with existing utilities. Slight adjustments in design can produce substantial cost savings by eliminating utility relocations. The definitions of the ASCE 38-02 Quality Levels A through D are provided in Appendix A. Further information on the processes to achieve these quality levels can be found within the ASCE 38-02 standard.

The project was divided into two phases:

- Phase 1: State-of-the-Art Review and Planning.
- Phase 2: Innovation Prototypes Development and Testing.

The overall work plan to fulfill the goals and objectives of the project consisted of eight tasks, with Phase 1 consisting of Tasks 1 through 3 and Phase 2 consisting of Tasks 4 through 8. The tasks were as follows:

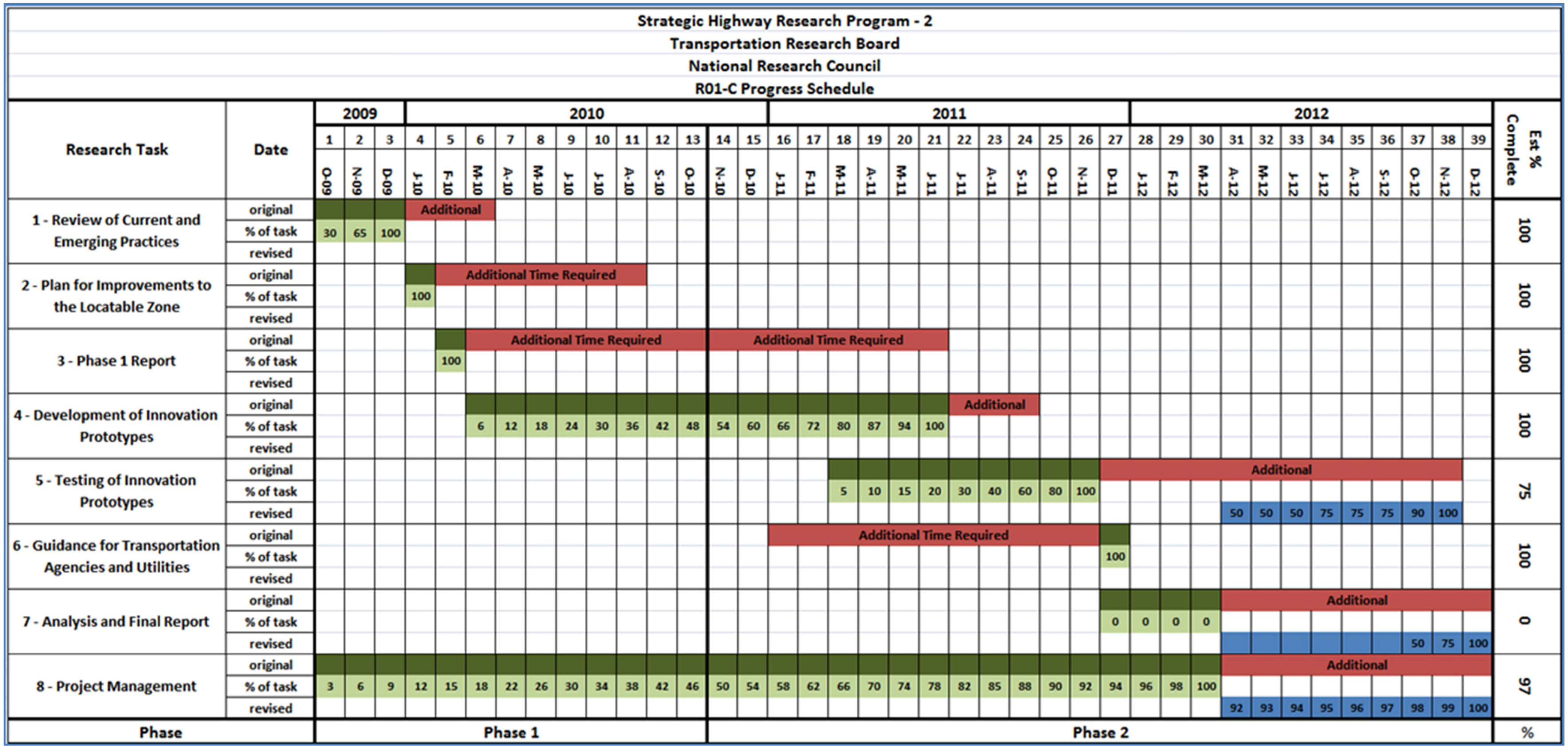
1. Review of Current and Emerging Practices.
2. Plan for Innovations to Improve Extent of Locatable Zone.
3. Phase 1 Report.

4. Innovation Prototypes Development.
5. Innovation Prototypes Testing.
6. Guidance for Transportation Agencies and Utility Owners.
7. Final Report.
8. Project Management.

The initial schedule called for 30 months to complete the eight tasks called out in the first amplified work plan, as shown in green in Figure 1.1. The cumulative delays that occurred during the course of the work required 39 months for execution. The variances in schedule by task are shown in red and blue in Figure 1.1.

It was also necessary during the course of the project to make adjustments in the project team. The final project team at the time of the R01C in-service testing consisted of the following organizations:

- Gas Technology Institute;
- Visible Assets Incorporated; and
- J. H. Anspach Consulting.



Strategic Highway Research Program - 2
Transportation Research Board
National Research Council
R01-C Progress Schedule

Research Task	Date	2009			2010												2011												2012												Est % Complete
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	
		O-09	N-09	D-09	J-10	F-10	M-10	A-10	M-10	J-10	J-10	A-10	S-10	O-10	N-10	D-10	J-11	F-11	M-11	A-11	M-11	J-11	J-11	A-11	S-11	O-11	N-11	D-11	J-12	F-12	M-12	A-12	M-12	J-12	J-12	A-12	S-12	O-12	N-12	D-12	
1 - Review of Current and Emerging Practices	original	🟩	🟩	🟩	Additional	🟥	🟥																																		100
	% of task	30	65	100																																					
	revised																																								
2 - Plan for Improvements to the Locatable Zone	original				🟩	Additional Time Required	🟥	🟥	🟥	🟥	🟥	🟥																													100
	% of task				100																																				
	revised																																								
3 - Phase 1 Report	original					🟩	Additional Time Required	🟥	🟥	🟥	🟥	🟥	🟥	🟥	Additional Time Required	🟥	🟥	🟥	🟥	🟥	🟥	🟥																			100
	% of task					100																																			
	revised																																								
4 - Development of Innovation Prototypes	original						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	Additional	🟥	🟥																100
	% of task						6	12	18	24	30	36	42	48	54	60	66	72	80	87	94	100																			
	revised																																								
5 - Testing of Innovation Prototypes	original																		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	Additional	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		75
	% of task																		5	10	15	20	30	40	60	80	100														
	revised																															50	50	50	75	75	75	90	100		
6 - Guidance for Transportation Agencies and Utilities	original																Additional Time Required	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩													100
	% of task																											100													
	revised																																								
7 - Analysis and Final Report	original																											🟩	🟩	🟩	🟩	Additional	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	0
	% of task																											0	0	0	0										
	revised																															🟦	🟦	🟦	🟦	🟦	🟦	50	75	100	
8 - Project Management	original	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	Additional	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	97
	% of task	3	6	9	12	15	18	22	26	30	34	38	42	46	50	54	58	62	66	70	74	78	82	85	88	90	92	94	96	98	100										
	revised																															92	93	94	95	96	97	98	99	100	
Phase		Phase 1													Phase 2																										%

Figure 1.1. Project schedule with variances.

CHAPTER 2

Research Approach

Phase 1: State-of-the-Art Review and Planning

In order to achieve the objectives in an organized manner, several tasks were performed during Phase 1 that informed and guided the execution of Phase 2. The two primary activities were:

- A technology review that assessed the state of the art in underground location technologies was performed based on the published literature. Time and budgetary constraints precluded interviewing experts in the field outside of the project team. The technology assessment also reviewed soil properties and the physics of wave motion to provide an understanding of why the selected technologies should improve facility location. This review was formalized as a report that was circulated to SHRP 2 and the technical expert task group (TETG). This report is included as Appendix B.
- A user panel was formed to provide guidance about the application of these technologies under real-world conditions. A set of key performance indicators (KPIs) was constructed for each proposed technology and provided to the user panel for review. The feedback from the user panel was incorporated into the technology development and field-testing plan. These KPIs and the feedback were used as guidance in the development of the technologies.

It also became apparent during the performance of Phase 1 that the efforts of R01B and R01C paralleled one another to a high degree. In addition, SHRP 2 Project R01A would make use of data generated by R01B and R01C. To this end, the three projects coordinated efforts in those areas that overlapped. The technology assessment covered the findings of both R01B and R01C, which also shared a common user panel (Appendix C).

Review of Current and Emerging Practices

In this task (Task 1), the project team collaborated to produce an amplified work plan and work breakdown structure (WBS) during the first 15 days after the activation of the project. This WBS laid out the roles and responsibilities of project team members in reasonable detail through the end of Phase 1. An amended WBS was developed for Phase 2.

The project team conducted a review of the technologies and practices currently available for locating and tracing buried infrastructure. The following is a nonexhaustive list of the technologies that were examined. The project team has collective experience in all of the technologies enumerated.

- Seismic and acoustic location.
  - Surface-launched seismic reflection techniques.
  - Introduction of an active acoustic signal to media inside of piping.
  - Passive detection of utility acoustic signatures.
- Ground-penetrating radar (GPR).
  - GPR at various frequencies.
  - Multiantenna arrays.
- Electromagnetic (EM) tracing of metallic utilities.
  - Introduction of active signal current onto the piping.
  - Induction of a signal onto the piping.
  - Passive detection of residual magnetic signatures on piping.
- Smart tagging, locating, and identification.
  - Advanced, long-range IEEE 1902.1 smart tags.
  - Location of legacy radio frequency (RF) tags at shallow depth.
  - Locate and read proprietary serialized tags.
  - Integration of smart tag reader with EM pipe locators.

A review of current and emerging practices identified a wide range of technologies developed globally that make performance claims with limited verified laboratory and field evaluation. Technologies that have existed for many years have not been able to penetrate the barriers of market entry to develop and support a sustainable business. Without the ability to enter the market, a technology will not be available for use by transportation agencies, even though the technology was successful during the proof-of-concept testing in the laboratory and the field.

Although the primary objective of this project was not to develop a commercialization program for the deliverables, it was essential that the research program be cognizant of market forces that would drive the deployment of the tools developed. Future transportation industry challenges will require advanced detection and accurate determination of buried utilities within an expanded current locatable zone. To avoid the waste of time and money on research to produce tools that never reach the user community, the research team collaborated with a team of industry advisers.

This user panel consisted of stakeholders that would be, or would contract with, end users of the locating technologies developed. The function of this body was to provide the end-user perspective early in the development process, not to provide feedback on the technical approaches. A joint user panel was developed for the R01B and R01C projects because many of the issues were the same for both projects. James Anspach, a consultant for both projects, was the primary organizer and recruiter for the user panel, with assistance from the principal investigators.

The project team used a model developed through the Civil Engineering Research Foundation (CERF) of the American Society of Civil Engineers (ASCE) in which several municipal evaluators committed to evaluating a pipeline condition assessment. These evaluators identified the KPIs that they determined to be essential to the successful adoption of the technologies. These KPIs became the baseline for establishing the commercialization potential and being able to develop a sustainable market. The user panel for the R01B and R01C projects represented a wide range of expertise, including transportation engineering and construction and Subsurface Utility Engineering (SUE). The user panel was designed to be geographically distributed and to represent transportation and utility agencies.

Task 1 Variance

During the early execution of SHRP 2, it was realized that there was a good deal of commonality between the R01B and R01C projects. The TETG, on reviewing the draft state-of-the-art assessments from both projects teams, determined that these could be combined into a single document. The first draft specific to the R01C project was submitted in December 2009. There were several revisions that added detail as requested by the TETG. The final combined technology assessment for R01B and R01C was issued in June 2010.

Plan for Innovations to Improve Extent of Locatable Zone

The primary goal of this task (Task 2) was to establish the metrics for the performance goals of the innovation prototypes. These metrics were based on the KPIs established through the collaboration of the user panel and the project team. The project team created a set of draft KPIs for the various technologies under development. The draft was reviewed and commented on by the user panel. The finalized KPIs were factored into the development of the innovation prototypes and the field testing.

GTI prepared a draft of the state of the art as per the findings of Task 1. This was reviewed by the project team to identify gaps and areas of improvement in the technology. The individual team members provided input in their respective areas. Another goal of Task 2 was to identify and contact other organizations engaged in similar efforts in order to prevent duplication of efforts. J. H. Anspach Consulting coordinated with the United Kingdom's Mapping the Underworld (MTU) research project and solicited comments from state DOTs regarding potential field sites at the American Association of State Highway and Transportation Officials (AASHTO) annual ROW and utilities subcommittee meeting, as well as from various SUE providers across the country.

Jim Anspach and Dr. Chris Rogers (University of Birmingham, MTU project) started collaborating in 2007. They kept each other informed of progress and joint research opportunities with the goal of leveraging strengths. Gary Young of UIT and Anspach also worked with Dr. Rogers during the execution of SHRP 2 R01B to coordinate efforts. Anspach was the liaison between MTU and both R01B and R01C.

Appendix C gives information on the joint user panel for the R01B and R01C projects. An invitation was issued to individuals identified by the project team as probable end users of the technology. Those accepting the invitation were provided with the KPIs for review. A user panel webinar was also presented by the various investigators to give more in-depth background. Finally, questions and feedback were solicited from the user panel.

Phase 1 Report

The Phase 1 report (Task 3) was produced by GTI with substantial input from the project team members and the project advisers. It contained the following sections:

- The current state of the art for locating and tracing technologies;

- The outstanding gaps and needs to address the objectives of the request for proposal (RFP);
- The KPIs articulated by the advisory group;
- The device performance requirements to meet the KPIs; and
- A detailed test plan of the activities required to fulfill these.

This report was proposed to be presented to the sponsor at the end of Task 3. The preparation of the report required more time and resource than originally anticipated. One of the prerequisites for the preparation of the report was the approval of the KPIs by the user panel; this process was delayed because it took longer than expected to get responses from the panel members. There were also several iterations of the state-of-the-art technology review that was a precursor to the Phase 1 report.

The first revision of the Phase 1 report was submitted in October 2010. There were several iterations and requests for additional material to be included. The final version of the Phase 1 technical report was accepted in May 2011. The report was substantially improved by the feedback of the TETG, which required additional technical detail in several areas.

The original planned start of Task 4 was to coincide with the end of Phase 1 as signified by the acceptance of the report. In the interest of keeping the project as close to the original calendar schedule as necessary, technical work was allowed to go forward while the Phase 1 report was still in revision.

Phase 2: Innovation Prototypes Development and Testing

The primary activity of Phase 2 was the construction and testing of innovation prototypes that were sufficiently robust for field demonstration. It was originally expected that several distinct prototype modules would be constructed:

- A seismic reflection module incorporating the following:
    - ○ Seismic reflection sources and sensors in a movable frame.
    - ○ The ability to map a 2-D survey line, or slice across a site.
- An active/passive acoustic locating module incorporating the following:
    - ○ A set of wireless sensors.
    - ○ An active acoustic source that can be attached to a pipe.
    - ○ Signal processing to determine depth and location from the sensor data.
    - ○ Signal processing to locate features from passive signatures, such as flow or 60-cycle hum.
- Smart tags with the following features:
    - ○ The ability to be located and read at depths up to 20 ft.
    - ○ Compliance with the IEEE 1902.1 communication standard.
    - ○ The ability to incorporate sensors and memory within the tag.
- An EM module was originally planned incorporating the following:
    - ○ An innovative technique for accurately locating buried metal.
    - ○ Odometry incorporating inertial navigation system (INS) and GPS technologies.

This was a logical partition of functions for the purpose of prototype construction. Higher levels of integration might be possible in a finished product but were outside the scope of this project. Not all the technologies in this list resulted in prototypes that were available for field testing. The following section addresses the technologies individually.

CHAPTER 3

Technology Development

Phase 2 dealt with the execution of the planning performed during Phase 1. Three distinct activities were carried out during Phase 2. Innovation prototypes were constructed and initial testing was carried out. On the basis of the results of bench testing and limited field tests, some of the technologies were eliminated from field testing. A series of presentations and documents were prepared to inform the end-user community of the efforts during this project. Finally, in-service testing was performed with two of the candidate technologies on a DOT site. This testing was witnessed by a SUE firm to provide independent feedback.

Innovation Prototypes Development

Seismic Reflection Locator

UIT was the primary subcontractor for the seismic reflection approach that was part of the development of prototypes (Task 4). The proposed research focused on imaging deeply buried utilities with shear wave (S-wave) seismic techniques. The research team believed the best targets were larger, deeper pipes, but testing was necessary to determine the detectable limits of size and depth. The team proposed using standard common midpoint stacking of S-wave seismic data as typically generated by seismic surveys. The cross section in Figure 3.1 shows a hyperbolic diffraction associated with a 54-in. sewer pipe at 38-ft depth. Hyperbolic diffractions are created when a survey traverses a linear or point target, similar to the signatures obtained with GPR surveys. The pipe image may not be as clear as desired, but the example shows the potential for seismic technology in an area where GPR can image only the upper 1 to 2 ft.

This pipe signature is diffuse because the seismic survey used lower-frequency hardware and standard imaging techniques normally used for deeper geologic mapping. The techniques require intense field effort and time-consuming data processing, making such surveys probably too costly for infrastructure mapping projects. However, UIT believes that with appropriate incorporation of new ideas, an S-wave system tailored to deep utilities can be developed. Modification of field techniques, measurement system hardware, and data processing methodologies could produce a system that is more field efficient for this purpose, less time-consuming, less costly, and most important, more effective at finding the deep targets. This system requires development testing because previous research on seismic properties of soils at the scale needed for utility mapping has been limited.

UIT used the results from the R01B project in which initial measurements of seismic properties of soils were made to optimize receiver specifications. The R01B project developed an S-wave seismic system for mapping dense, shallow networks of utilities. This project intended to use similar techniques and develop instrumentation and analysis techniques that could be complementary to the R01B project.

The technology used accelerometers as receivers to improve higher-frequency data quality. As stated above, the old system was unable to collect high-frequency data because of the geophone receivers used. The signal sources for this project were electronically driven impact sources of two different sizes. The larger source was used to collect lower-frequency data for large-scale velocity analysis, and the smaller source was used to collect shallow velocity data, as well as reflection data, for imaging the target. Having a more complete knowledge of velocity over the depth range of interest allows accurate calculation of target location and depth.

The methodology chosen for this part of the project was an attempt to find a technology, unlike GPR, that will image a small target over a depth range of 0 to 50 ft. In some cases, it is possible to use GPR for finding deep utilities, but often GPR waves do not have the necessary depth of penetration. GPR signals are subject to attenuation, especially in clay soils, that vastly decreases depth of penetration. Also, for deep utilities, lower-frequency GPR signals are necessary, and antennas to operate at the lower frequencies are often no longer

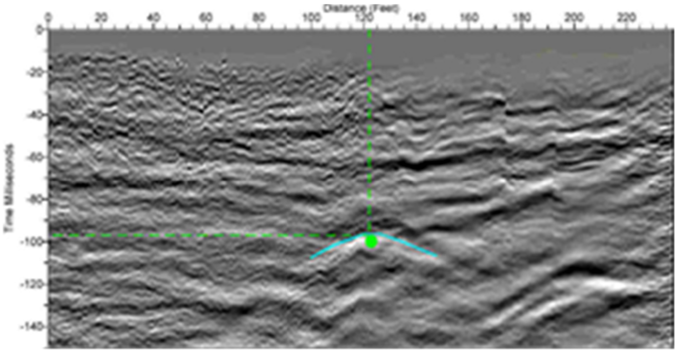


Figure 3.1. Stacked S-wave return data.

available because of FCC regulation of the frequency bands and power levels (lowering the frequency requires raising the power to maintain the same performance). Very low-frequency GPR antennas are not shielded because of their size, allowing noise from outside sources and reflections from surface objects to contaminate the data. In searching for a measurement technique to serve the project's purpose, the seismic techniques appear to be good candidates. As seen in Figure 3.2, seismic techniques have shown technical success in mapping a target that is of interest in this project.

Seismic Analysis Techniques

Several possible seismic techniques are available. P-wave refraction and reflection, S-wave refraction and reflection, and surface wave techniques are all currently used for various purposes in the industry. In choosing the best one for the proposed project, it was important to keep the depth range and target size in mind, but the research team also considered detailed technical aspects of the measurements, such as wavelength, capability to generate the frequencies needed, attenuation in the types of soils expected, and data acquisition system parameters. Separately, the team considered data processing, imaging, and interpretation matters as well.

Refraction and surface wave techniques are commonly employed to measure depth to layers such as water table, bedrock, and geologic layers of interest. They tend not to be effective at detecting, locating, or mapping small linear targets such as utilities, thus leaving P-wave reflection or S-wave reflection as candidates. Choosing between these two is complicated. However, it has been shown that shorter wavelengths are important for detecting smaller targets. Thus, the team wanted to keep the wavelength as short as possible. Wavelength is a function of the velocity at which the wave travels through the soil. Typically, the smallest target that can reliably be detected by a wave will have a diameter equal to about one-quarter of the wavelength.

Figure 3.3 shows quarter wavelengths of three kinds of waves in soils the research team would likely encounter: GPR (for comparison), S-waves, and P-waves. The values in the figure are computed using parameters that represent "good" soil conditions for each technique. In suitable soils, GPR has a very good detection capability. The task is to find a technique that can do as well in other soils not suitable for GPR. Seismic waves tend to be more suited for soils that are wet and clay rich, so they are a good complement to GPR. The figure demonstrates that the overall S-waves mimic the wavelengths of GPR well under the assumed conditions.

Because it is generally easier to generate source waves that are lower in frequency (similar to common GPR wavelengths), the team decided to use S-waves instead of P-waves. It is necessary to generate and propagate S-waves in the 200- to 700-Hz range to have 10- to 2-in. target diameter detection capability. Based on experience, the team could readily generate waves in this frequency range. Achieving a detection capability of as small as 2-in. diameter with P-waves requires generating frequencies of at least 3,000 Hz, which tends to be difficult, and they deteriorate quickly with distance.

The original approach to designing the S-wave sources was based on mathematical modeling of the soils-to-source interaction. From the R01B project, a large database of seismic-wave velocities in soil was amassed to populate the model. The performance of the model was not adequate. Seismic components were redesigned and tested empirically. One round of functional testing was completed in the Houston area.

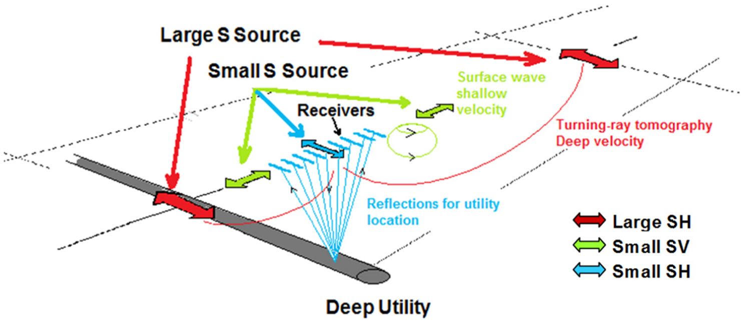


Figure 3.2. Seismic reflection concept.

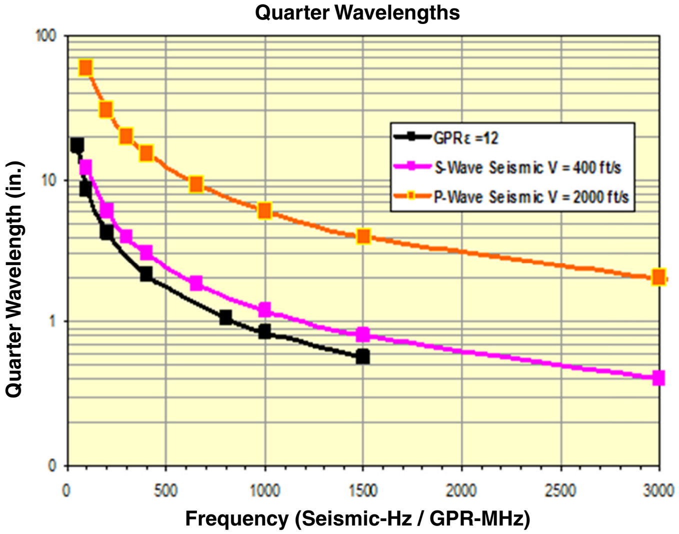


Figure 3.3. GPR versus seismic quarter wavelengths in soil.

It became clear during the course of the project that no innovation prototype for seismic reflection technology would be ready within the schedule and budget of the R01C project. This technology was not included in the field-testing task. As of this writing, UIT continues work on this technology outside of the SHRP 2 projects.

Appendix D contains additional technical support information for the seismic reflection technology.

Active Acoustic Locator

GTI proposed to develop a portable, active acoustic pipe-location prototype suitable for proof-of-concept testing on natural gas and water mains and sewers/sewer laterals or any open conduit. This work endeavored to use a common technology platform with the seismic reflection technique for the sake of economy. In the active acoustic technique, a known signal is injected into the medium being carried by the pipe. The known signals are generated by an acoustic driver connected at the service of a natural gas line, a water hammer generated at a hydrant, or an acoustic driver hanging in a sewer manhole. The acoustic wave propagates through the medium in the pipe, not along the pipe wall. However, as the signal travels through the medium inside the pipe, be it liquid or gas, a portion of the signal couples into the pipe wall. Vibrations from the pipe wall propagate to the surface of the ground, where they are detected. In applications where the appropriate signal can be injected, the prototype should provide the operator with the location and depth of the buried utility.

The prototype was based on two technologies previously developed and patented by GTI. The first was an active acoustic technique for locating plastic pipe. The second technology was field-portable acoustic hardware developed to pinpoint buried leaks, along with algorithms to eliminate interference. Field crews successfully used this hardware, shown in Figure 3.4, to pinpoint small natural gas and steam leaks in the presence of substantial background noise.

Figure 3.4. GTI digital acoustic leak detector.

Active Acoustic Signal Injection

The prototype used two techniques to locate the pipe: amplitude and time of flight (TOF). The amplitude technique relies on the signal strength to localize the pipe. Because the injected signal is known, correlation signal-processing techniques can be used to discriminate the pipe-location signal from background noise. The TOF technique uses an acoustic signal composed of a series of bursts of a known waveform, with each burst separated by silence. This provides a different advantage: the technique is less susceptible to variations in coupling between the sensor and ground. Laboratory instrumentation powered by an inverter was used to verify the TOF technique. Portable hardware needs to be developed to apply the technique. In addition, lower frequencies need to be used to increase the depth of detection. The key technical issues to be solved are development of accurate depth-location algorithms.

Measurements were made at GTI's pipe farm facility, and at the Talbotton Road test site in Georgia. The depth of application was extended by using lower frequencies. The sensor package from the passive leak detection unit was modified for use at a frequency range centered around 300 Hz as opposed to the original 1,000 Hz. Each sensor, its signal-conditioning electronics, and the radio are housed in a single unit. The digital signal processor used in the leak pinpointer was replaced with a more energy-efficient model. The goal was a unit with a reasonable form factor and long run times between recharging.

An acoustic driver was developed for use in empty pipes. The driver converts the signal from the main unit into sound. A device was also proposed that creates water hammer pulses and is equipped with a sensor to relay the water hammer signal to the prototype central processor; this device was not put into practice because of time and budgetary constraints. The prototype was programmed to use both the TOF and the amplitude techniques. The main unit was programmed to automatically interpret the results, display them, and give the operator instructions for the next step.

Passive Acoustic Detection

GTI also believes that this prototype can perform passive detection of the acoustic signatures of various utilities. Passive noises include flow noise generated by natural gas or water flowing through the pipe or acoustic hum generated in electrical cables. Three-phase electrical cables are designed to minimize the electrical field around them. However, interactions between the cables generate large acoustic vibrations that can be detected at a distance. Because the frequencies are similar, the passive and active techniques can be implemented with the same sensors, signal-processing hardware, and readout display. The exception is that the active technique requires injection of a signal.

Seismic and Acoustic Compared

One of the overall goals of the project was to develop a suite of complementary technologies. The seismic reflection method has the advantage at locations where the buried facility is inaccessible. The active method has some advantages over the seismic reflection method in those instances where there is access. Because the acoustic signal only travels from the piping to the ground surface, it suffers less attenuation. The active signal is injected into a particular pipe; therefore, the pipe is positively identified. The signal originates in the pipe instead of reflecting from its surface, relaxing the requirement that the wavelength must be scaled to the pipe diameter. The active method can use lower frequencies, which suffer less attenuation to achieve extra depth. Active acoustic location of water mains was expected to be particularly effective because of the large signal expected from a water hammer tool and because of the high conduction of sound through water. Likewise, the passive acoustic technique was expected to be effective on live electrical cables.

As a result of time constraints, the demonstration system used a laptop rather than an embedded system display to display the pipe location and depth results. This version of the hardware underwent preliminary testing at a site in Manteno, Illinois. The results of the testing were used to make adjustments to the prototype preparatory to further field testing.

The output of this task was an innovation prototype system that can locate buried pipelines by injecting an acoustic signal into the medium within the pipe. Depth estimation is available in the active signal injection mode. Depth estimation is not supported in the passive mode.

Appendix E contains additional technical support information on the active and passive acoustic locating technology.

Scanning Electromagnetic Locator

GTI proposed to develop a portable electromagnetic (EM) pipe-location prototype suitable for proof-of-concept testing on metallic natural gas and water mains and sewers/sewer laterals. In this EM technique, a rotating EM field is projected into the soil containing metallic pipes. The projected field induces eddy currents in metallic objects, which in turn produce a detectable field. The rotating field is generated by a set of driven coils, so phased as to gradually rotate the driven field through 360° about a central axis. The primary frequency of the EM signal and the rate of the field rotation are independently adjustable. The concept is shown in Figure 3.5. One or more sensing coils monitor the EM field as it rotates. The sensing coil signals are captured, along with the angle of the

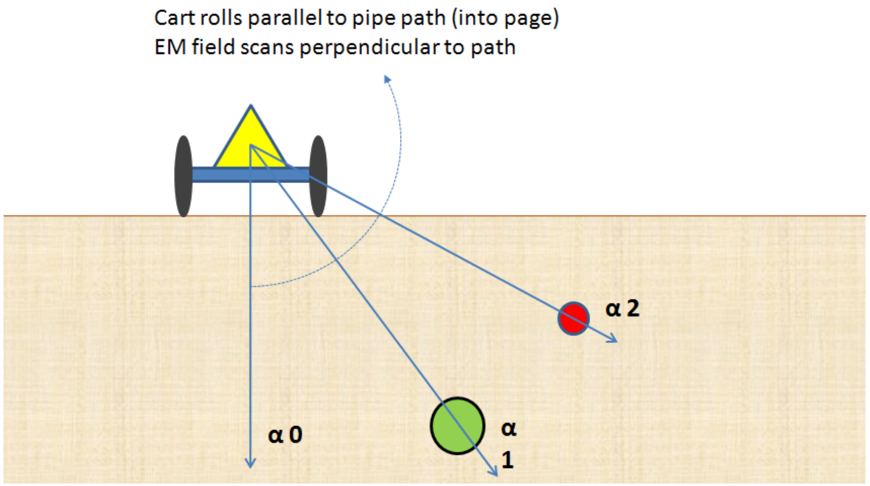


Figure 3.5. Scanning EM locator concept.

rotating EM field. Metallic materials within the range of the instrument disturb the EM field as seen by the sensing coils.

The location of the buried metallic facilities would be in cylindrical coordinates referenced to the prototype. This would allow the EM innovation prototype to be used in two distinct modes: deployed on the surface along the path of interest or within a nonmetallic pipe.

When used from the surface, the prototype could detect metallic objects in a semicylindrical volume beneath its path, allowing adjacent facilities to be resolved more readily than would be possible with standard EM locators that place a signal on a single facility.

EM Prototype Implementation

The prototype was based on the metallic joint locator (MJL) previously developed by GTI and successfully used to pinpoint metallic joints, repair clamps, and service tees on natural gas pipelines. The MJL, shown in Figure 3.6, produces a stationary AC magnetic field oriented directly down into the earth. This requires crews to move the MJL over a large area to locate features or have some prior knowledge of the pipe location. The rotating field prototype allows a wider area to be scanned with each pass. The proposed work was to introduce the rotating magnetic field technique, modulation techniques for the EM field, and signal processing to trace buried pipes. The modulation techniques to be evaluated were polyphase sinusoids and pulse or single-phase sinusoids modulated by a polyphase sinusoid. These modulation techniques, in conjunction with multiple drive coils, produce the angular rotation of the EM field axis. The primary EM frequency is limited to 200 kHz or lower, based on prior experience using AC electromagnetic methods. A balance needs to be achieved between the depth of signal penetration and the size of facility detected.

Figure 3.6. GTI metallic joint locator.

The expected result of the active EM technique was a working innovation prototype for detection, lateral location, and depth estimation of metallic buried facilities. A method of tracking the linear motion would be incorporated into the data and their presentation. The proposed means of linear odometry was the combination of INS and GPS technology. Signals sent into the ground, data from the sensors, and the processed signals could be stored for later review.

The prototype of the scanning EM locator, shown in Figure 3.7, experienced several difficulties. There were signal strength issues related to crosstalk between the channels. The three-phase emitter coils and the pair of three-phase pickup coils have a degree of mutual coupling. The mutual coupling of the pickups degraded the angle-to-target resolution somewhat. This issue was exacerbated by the fact that the pickups were tuned to a specific resonant frequency: the same frequency at which the emitter was driven. The resonance provides some additional gain, but the coils go on “ringing” after the field has swept through their position. Simply increasing the output power of the emitter does not improve the range or signal strength.

A solution was tested that used nonresonant coils with an additional preamplifier to compensate for the lost resonant gain. This improved the situation somewhat, but the best solution was judged to be to migrate to a two-phase design with completely orthogonal coils. This solution would have required substantial reworking of the prototype hardware and software and could not have been completed within the resources of the current project. GTI believes that the basic technique is viable based on the performance of the commercial MJL available from Sensit Technologies.

The output of this task was not available during the current project. The EM innovation prototype that uses a new technique to accurately locate buried metallic utilities and objects requires additional development before field testing

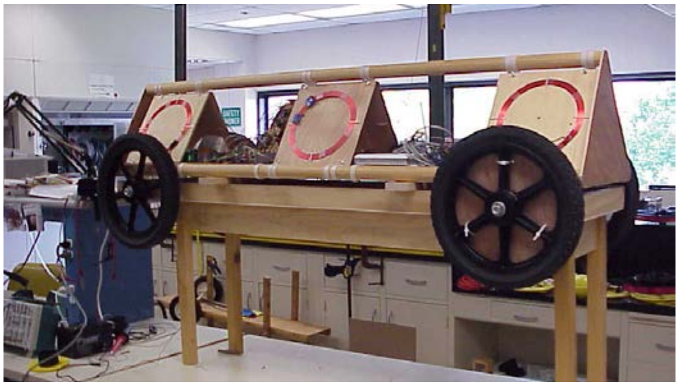


Figure 3.7. Prototype scanning EM locator.

can be performed. The level of effort required to complete this prototype puts it outside the scope of the R01C project.

Appendix F contains additional technical support information on the scanning EM locator technology.

Long-Range Radio Frequency Identification Tags

VAI proposed to create a long-range pipe-location network based on a public wireless standard, IEEE 1902.1. The tag network has the advantage of cost-competitive marker tags that can be placed in both new and existing installations, with detection ranges of up to 40 ft underground, allowing sufficient margin that a marker at a depth of 20 ft has a reasonable "aperture of discovery" aboveground. The pipe tag transforms a buried plastic pipe into a smart pipe that can report location and status.

The pipe tag could be built into the pipe, with optional sensors, and small portable readers could harvest key information directly from the tag, as well as feed into a real-time geolocation database. There is some scaling of the device range with the size of the antenna. Tags for near-surface pipes could be quite small, as shown in Figure 3.8. A tag for a deeply buried sanitary or drain line may need to be 6 in. in length. Given the size of these deeper mains, building the device into a standard section still presents a negligible footprint. The final production versions of the tag would need some means of ensuring their orientation with respect to the facility; the prototypes would not have this. A tag permanently built into a pipe could be aligned with its axis to provide an operator with information on the direction of the pipe run. A tag installed in an "after the fact" excavation would need some sort of leveling mechanism to provide the best signal strength.

IEEE 1902.1, or RuBee, is an international wireless visibility standard. RuBee is not simply radio frequency identification (RFID) in that it is a two-way, peer-to-peer transceiver protocol, and it can optionally use smart tags with small processors and sensors. RuBee has been optimized for visibility applications that must work in harsh environments, underwater or underground, and near or on steel and that may also require high security, high human safety, high intrinsic safety, and low electromagnetic interference. RuBee is not like RFID. It is a packet-based protocol that operates at 131 kHz; most of the energy at these frequencies is magnetic. RuBee is the only wireless technology that provides long-range read/write in harsh environments.

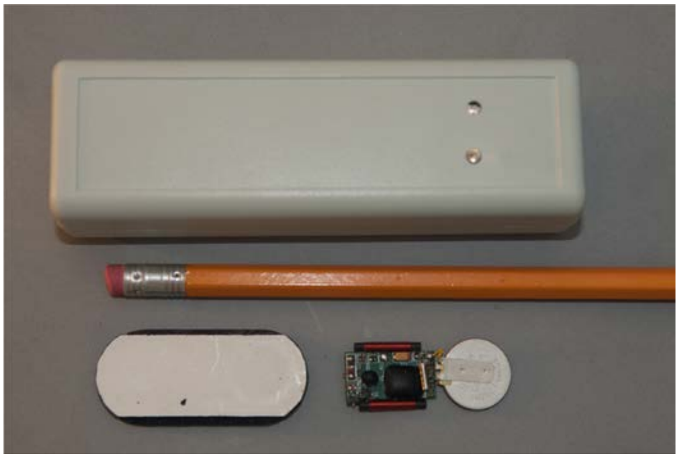


Figure 3.8. Various RuBee tag form factors.

VAI has developed a smart tag that has a detection range of more than 40 ft. The tag costs less than current passive marker tags and has an expected battery life of more than 20 years, with the possibility of extending that to 50 years.

VAI was slated to create two focused prototype tag products for this project:

- *Hardened RuBee marker tags (RMT).* These tags are waterproof and explosion proof, meet ANSI/UL 913-88, are designed for an underground life of 50 years, and have a range sufficient for utilities at 20-ft depths. Tags programmed with three-axis location data and, optionally, other relevant information about the buried assets can be placed into a construction site trench and near or on top of a pipe or other asset. These tags can be used for new construction, as well as with existing pipes that have been excavated.
- *Hardened RuBee pipe tag (RPT).* RuBee tags were proposed to be attached directly onto a pipe or fabricated as part of the pipe, either inside or outside. Tags would have the same basic specification as the RMT tags; however, the form factor would be conformal to the shape of the pipe itself, with a long-term goal of manufacturing the tags as part of the pipe.

VAI produced two smart tag interrogation devices for this project:

- *Commissioning handheld (CH).* A short-range (2 ft) read/write handheld device with barcode reader, RuBee reader and writer, Wi-Fi link, and software capable of adding useful information to the tag, as well as setting data values, such as current GPS coordinates, expected depth, date and time of installation, pipe type, size, content, and other field-critical data. Including field-critical data offers savings on future field localization, since the user would not require access to a database. In times of emergency or even routine localization, local data storage offers many advantages.
- *Tag localizer (TL).* A long-range (5 to 70 ft) read/write and presence-detection portable reader that can locate tags and provide field-critical data from both tag reads and a remote database (Dot Tag server) capable of providing the same details. The TL may also provide real-time localization of the tag based on tag signal and two antennas. The TL may

be attached to a vehicle or may be hand carried. It will include GPS and GPRS data link.

The production of smart tag technology prototypes was delayed by a number of factors. VAI proposed that the performance of the tags could be improved by reducing the design to a single-chip implementation. The layout and first production of the new chip was expected to be completed during the second quarter of 2011, but there were multiple delays in the production of the new silicon. The fallback position was for VAI to provide engineering samples for demonstration based on their earlier chipset. This was executed, and VAI produced 20 sample tags with a range in excess of 40 ft, along with two handheld reading devices. Preliminary testing took place in a borehole 20 ft deep. The soil had no impact on the operation of the system. Several samples and readers were delivered to GTI; examples are shown in Figure 3.9. The balance of the hardware was available for Task 5 testing.

The outputs of this task were working models of a buried smart tag that have ranges appropriate for utility depths of 20 ft, handheld devices to interact with the tags, and the appropriate system software. This system will allow operators to accurately relocate facilities at a lower cost than current GPS systems. Additionally, the tags provide positive identification of the buried facility via a unique serial number.

Appendix G contains additional technical support information on the long-range smart RFID technology.

Internal Inertial Mapping System

On the basis of the required improvements identified in Task 2, an innovation prototype inertial mapping tool for internal deployment in piping was proposed for development. Several areas of research and improvement were identified. These included the following:

- *"Live" insertions.* Requiring the utility to be shut down and taken out of service before running inertial mapping tools is a significant limitation. Many lines cannot be shut down, because of the critical nature of their services. Developing a technique that allows the inertial mapping tools to be installed through a "hot tap" would increase the application and practicality of using inertial mapping for locating deeply buried utility lines.
- *Smart tag internal benchmarking.* The ranges of inertial mapping tools are limited by cumulative error; the accuracy slowly degrades with distance from the insertion point. Smart tags are an excellent technology for locating deeply buried utility lines, but installing the tags requires access to the utility. If the inertial mapping tools could also be used to install smart tags on the interior of a pipe wall, relocating these facilities in the future would be greatly simplified. Smart tags could be used as a benchmark to enhance the accuracy of inertial mapping.
- *Small hole insertion.* Excavation and restoration costs are a significant factor in determining the practicality of using inertial mapping tools. Developing installation techniques that reduce the size of the excavation, and therefore reduce the total cost of use, would also increase the feasibility of this technology.

Figure 3.9. VAI long-range tags and handheld reader.

The original plan was to perform a demonstration of the existing smart probe inertial mapping system in out-of-service facilities. This was to be a demonstration of the inertial mapping capabilities only and did not include any of the live insertion aspects. After consideration, however, SHRP 2 and the project team concluded that there was no longer a research component to this particular subtask. Inertial mapping technology was dropped from the testing program.

Appendix H contains technical support information on the use of inertial mapping technology for the internal mapping of ducts.

End-User Outreach and Presentation

Over the course of the R01C project, a substantial number of presentations and outreach documents were prepared. The audiences for these materials were varied. Some of the materials were targeted at groups directly involved in the project, such as the utility advisers and the TETG. Others were presented in public forums, such as the TRB annual meeting, the AASHTO annual ROW and utilities subcommittee meeting, and several well-attended utility webinars. The purpose of the public outreach was to keep the community of potential end users informed about the progress of R01C, as well as to collect feedback on the direction of the project.

User Panel Selection and Interaction

A user panel was formed during Phase 1 to serve as an audience and review body for both R01C and R01B that would be representative of those who would use the tools or products resulting from this work. A set of KPIs was formulated for each of the technologies and reviewed by the user panel (Appendix C). A general information webinar was presented to the user panel in September 2010. A final products summary and presentation was prepared in April 2011 and reviewed by the user panel.

TRB Annual Meeting Workshop

A workshop for the SHRP 2 R01 projects was presented at the TRB annual meeting in January 2011. It included the following elements:

- An overview giving the motivation for the SHRP 2 projects;
- A presentation on R01A (geospatial data repositories);
- A presentation on R01B (multisensor platforms for subsurface 3-D imaging);
- A presentation on R01C; and
- A presentation on the MTU project.

TETG Webinars

The first TETG webinar took place in July 2010. This webinar acquainted the TETG with the concepts for technology prototypes that were being tested and the proposed schedule. Additional TETG webinars were held during the course of the project to keep the TETG apprised of progress and changes that occurred. The last of these was held in November 2012.

Utility Webinar Presentations

Two webinars were given in an open forum for any utility or state agency that wished to attend. These webinars were promoted through the TRB website. The purpose of the webinars was to promote the results of the R01A, R01B, and R01C projects and also to get feedback from the potential end users of any tools resulting from this work. Attendees of these webinars were able to post questions; the entire list of questions with answers by the appropriate researcher was made available after the webinars.

The first utility webinar took place in August 2011 and attracted just over 300 registrants. There were also 31 questions, comments, or suggestions posted during the webinar. A poll of the attendees indicated that over 90% of the attendees were satisfied with the content and presentation. The second utility webinar took place in February 2012, with an estimated 186 attendees. The level of satisfaction and questions were comparable to the first webinar.

AASHTO Presentations

Presentations were given at the AASHTO annual meeting in May 2011 and again in April 2012.

CHAPTER 4

Prototype Field Testing

Innovation Prototypes Testing

The primary objective of this task (Task 5) was to verify that the performance of the innovation prototypes satisfied the key performance indicators (KPIs) articulated by the user community during Phase 1.

Experimental work was performed with laboratory-grade hardware to determine the optimal parameters to obtain good depth and location accuracy. Data were collected on a variety of piping types before the in-service testing. This was an iterative process, with improvements made to the various prototypes based on these preliminary tests. Measurements were made at GTI's pipe farm facility, VAI's buried pipe facility, Staking University in Manteno, Illinois, and various other available sites.

The project team invited the user panel to provide input during testing. Since it was expected that the panel members would become the champions for transitioning the prototype from the laboratory to the user community, it was essential to integrate their input into the laboratory testing. Two members of the user panel were able to attend the in-service testing of the technology prototypes.

The project team members used their contacts to solicit appropriate field-test sites.

- Several SUE firms were contacted for a list of current or recently completed mapping projects that met criteria for the application of the innovation prototypes for extending the locatable zone.
- The site criteria included, but were not limited to, the following:
    - Utilities known or expected to exist at a depth past which the SUE firm's standard techniques did not work;
    - A diverse mix of utility types;
    - Utilities stacked directly underneath another utility;
    - Deep utilities for which the team had an ability to attach an RFID tag and subsequently detect it from the surface or through another deeper but accessible structure;
    - Diverse soil types; and
    - Diverse soil moisture/water table depths.
- That list was used to select several sites of geographic and condition diversity. The most important factor in site selection then became the cooperation of the state DOT for factors including the ability to get applicable permits to work in the ROW and assistance with necessary traffic control.
- The project team, in conjunction with the SUE firm, tested the technology at only one site.
- The user group was encouraged to observe the field test of the innovation prototype.
- The SUE firm was tasked with developing a written report of its observations.
- The project team developed a report outline for the SUE firm to follow, but left the content up to the firm.

Seismic Reflection System Testing

Limited shakedown testing of the seismic reflection prototypes was carried out in the Houston area, as shown in Figure 4.1. On the basis of the findings of the shakedown testing and other data collected, it was decided not to pursue in-service testing. The research that had been done so far was largely aimed at determining the basic physical properties (seismic velocity and wave attenuation) of S-waves in soils when using frequencies in the range of 100 to 1,600 Hz. This work was performed because no literature exists in this area of study, and without knowing these parameters the project team could not establish the specifications for seismic measurement and imaging systems. The velocity characterization was carried out with analytical instruments rather than the prototype.

The project team found three basic results in this work. First, that velocity and attenuation of S-waves in a wide range of soils are within ranges that are possible to measure with the capabilities of modern electronic components, such as

Figure 4.1. Seismic reflection initial prototype.

analog-to-digital converters and amplifiers. Second, the tests demonstrated that most of the time the team could generate and propagate S-waves in the subsurface soils within the frequency range of interest. In some cases, the linearity of soil behavior was in question, and further testing to track down this variable needs to be done. Lastly, the team determined that subsurface soil environments are even more complex and heterogeneous than expected.

Figure 4.2 shows the estimated depth at which various pipe diameters could be located using the seismic reflection technique. This estimate was generated using S-wave velocities measured in soils in combination with an analytic model of wave propagation in soil. The limit of detection is the point at which the line for the particular diameter in inches crosses the −120-dB attenuation line. This graph represents the case where the shear seismic wave is polarized parallel to the pipe being located; any misalignment will degrade the performance. It must also be noted that the solid lines represent soil calibration data, while the dotted lines represent extrapolations based on these data. In this

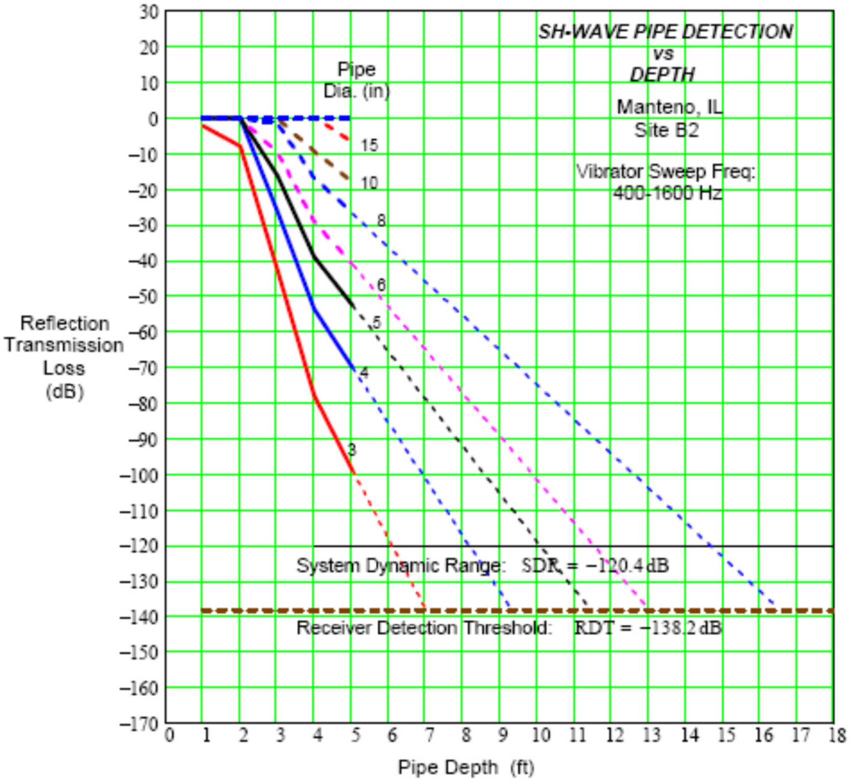


Figure 4.2. Estimated seismic performance in soil 1.

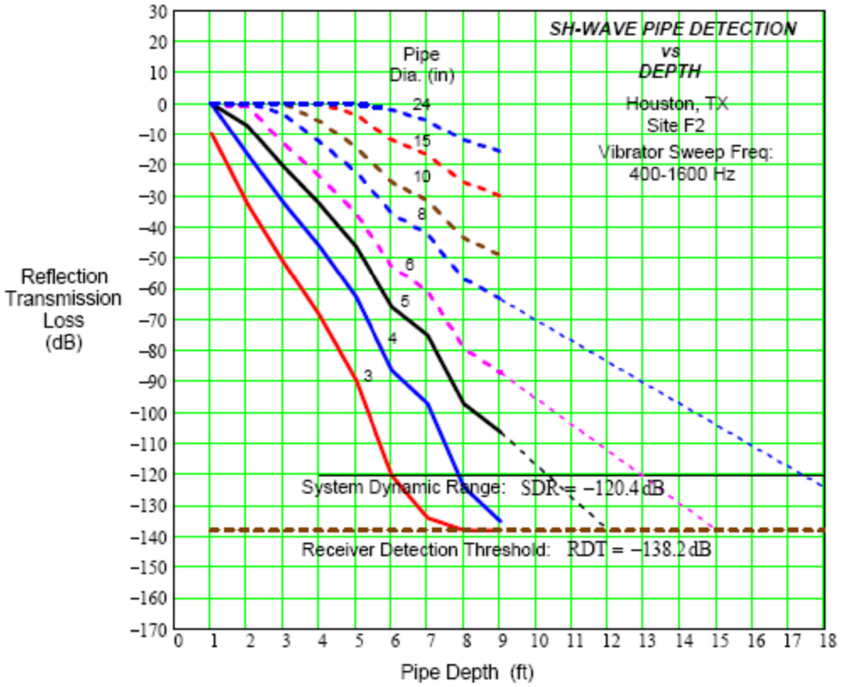


Figure 4.3. Estimated seismic performance in soil 2.

particular soil type, there were several instrumentation issues that prevented capture of deeper data. This degree of extrapolation highlights the amount of practical prototype development that remains before a field instrument can be deployed.

Figure 4.3 shows a similar data set for a dryer, stiffer soil than in the previous case. In this instance, it was possible to capture soil wave velocity data to a greater depth. The same constraint of the S-wave being parallel to the pipe is assumed. Once again, this estimate was generated from an analytic model that was populated with measured velocity values from the soil in question. The velocity data were captured with research-grade instrumentation, not with a technology demonstration prototype.

These observations had the effect of requiring more work than expected in structuring and operating sources, constructing receiver arrays, and performing data processing. This work could not be done within the project's original goals, time, and budget.

The following is a suggested outline for future development of a seismic system:

1. Construct and test a pulse type S-wave source generator.
2. Modify the source and receiver field carriage from the R01C project to accommodate the new source and to take into account data from the field tests.
3. Interface to a commercially available receiver that has come on the market since the project hardware was considered earlier.
4. Test this new setup over several sites with different soils and utilities.

Active Acoustic Locator

Testing of the Acoustic Locator in Manteno

Figure 4.4 shows the data acquisition board from Measurement Computing with the existing radio receiver. A laptop (not shown in the figure) connects with the data acquisition board via USB and captures the digitized signals. The MATLAB algorithms for pipe depth and location are then run on the

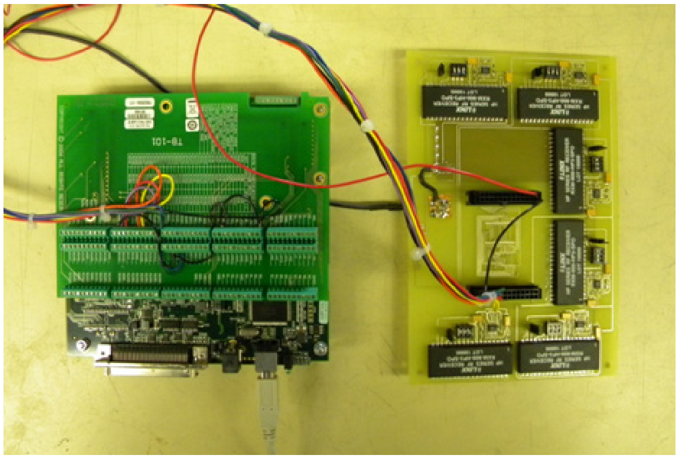


Figure 4.4. Acoustic data acquisition board with 6-channel receiver.

laptop. The algorithms had been verified as working correctly, and a user interface is provided on the laptop. This system was packaged and tested in the Manteno, Illinois, facility during November 2011.

The Manteno test site provided access to both ends of a 300-ft-long, 4-in.-diameter steel pipe. The pipe was initially believed to be full of air. However, the acoustic input signal could barely be heard at the far end of the pipe. This and subsequent measurements indicated that the pipe had a water blockage of unknown length at the low point. This blockage limited the amount of useful data that could be collected. Overall, the equipment functioned well. GTI learned a few practical improvements that should be made. For example, while the tripod sensors worked well on pavement, the spikes need to be longer to improve coupling in grass. The range of the radios needs to be checked again. Placement of the sensors started close to the injection point. The distance was gradually increased. At a distance of about 150 ft, the project team stopped receiving strong signals. This may be the result of a battery life issue, or it may have been due to water in the line blocking the signal. On the basis of the analysis in the field, the team appeared to be getting reasonable signal strengths up to the 150-ft point on the line being surveyed.

The data acquisition system in its enclosure is shown with the display laptop and audio amplifier in Figure 4.5. The amplifier drives a specialized speaker that is mated with the end of the pipe being surveyed (Figure 4.6). The survey line of wireless sensors is then moved progressively farther down the pipe being located. The data collected during this set of experiments were stored on the laptop for postanalysis.

Testing of the Acoustic Locator In-Service

This section discusses observations about the acoustic locator experience in the field (in Columbus, Georgia). The system is complex in the sense that there are many components to keep track of. These consist of the following:

- A rugged speaker with adapters to mate it to various diameter pipes;
- Six acoustic sensors with integrated radio transmitters;
- One data receiver with data acquisition system;
- A laptop tethered to the data receiver; and
- A power amplifier, also tethered to the data receiver, to drive the speaker.

Figure 4.5. Active injection equipment being tested at Manteno.

Figure 4.6. Acoustic signal injector on 4-in.-diameter pipe.

A laptop was used as the display for the first-round testing in the interest of meeting the schedule. Some effort had been expended in integrating the display and processing into the data receiver system, but this was dropped when it became clear that this could not be ready in time for field testing. The power amplifier could also ultimately be integrated into the data receiver, further reducing the number of components. The six sensors and the speaker driver would remain separate components in any implementation.

The actual user interface is simple; there are few menu choices. The sensors need to be laid out so that they are distributed along a line with known spacing. The accuracy of the sensor spacing does affect the accuracy of the depth estimate.

The current incarnation of the software runs slowly in the time-of-flight (TOF) mode. There are two processes that drive this issue. The actual processing of the TOF data is resource intensive and is currently implemented in MATLAB. Migrating the system to a faster processor running embedded code could significantly reduce the run time. This is a commercialization step and beyond the scope of the current project.

Another issue is that all the data generated during the operation of the prototype is saved to the hard disk of the laptop, adding more time to each run. This is critical for the prototype testing because it provides a measure of the system performance and a means for troubleshooting problems. Archiving the run data could be eliminated from a commercial version of the acoustic locator, but it must remain during the prototype development stage.

Overall, the initial field-test experience with the acoustic locator was poor. One false positive was generated on the first day of testing. Several other tests were run in areas where the facility being located was reasonably well known. The acoustic instrument provided depth estimates of 40 ft for facilities that were known to be between 5 and 6 ft deep. No other excavations were made on the basis of data from the acoustic instrument. The suspected problem is that at least one of the acoustic sensors was damaged in transit.

The first acoustic readings were taken on a sanitary line from a public restroom near 28th Street and Talbotton Road in Columbus, Georgia. A clean out on one side of the building was opened, and the speaker was inserted (Figure 4.7). The sensor array was placed near the curb on the 28th Street side. The presence of a sanitary line in this area was indicated (incorrectly as it turned out) by existing One-Call paint marks. A nominal center was found by using the amplitude method and depth shots taken. The depth estimate was 1 ft; this reading was consistent for array spacing of 1, 2, and 3 ft. The dig at this point resulted in a dry hole down to past 3 ft.

The line was then traced using a fish tape and EM locator. The run was discovered to go in the opposite direction to what was originally thought. The line went northeast and parallel to Talbotton to a second clean out and then made a right-angle turn into Talbotton and into a manhole. The manhole cover was removed and the end of the fish tape visually identified about 5 ft below grade.

The sensor array was placed in the grass along the Talbotton curb line, straddling the pipe path between the second clean out and the manhole (Figure 4.8). The signal was again injected into the first clean out because the project team was unable to safely open the second clean out. Despite placing sensor 3 directly over the expected pipe path, sensor 2 gave the highest reading and sensor 3 the lowest using the amplitude method. When the procedure was repeated with the TOF method, sensor 4 gave the highest reading, and sensor 3 was still the lowest. This procedure was repeated with the sensors 6 in. farther back from the pavement and also on the pavement. In all the cases, sensor 3 gave the lowest reading. A depth estimate from this location came back at 40 ft. Given the far end of the line was clearly 5 ft deep at the manhole, no excavation was made based on these data.

Figure 4.7. Signal injection speaker in clean out near 28th Street and Talbotton.

Figure 4.8. View from second clean out toward Talbotton Road.

Sensor 3 was opened and examined; no obvious problem was detected. The sensor array was moved to straddle the line connecting the two clean outs. Again, sensor 3 was so placed as to be on the projected location of the line. This time sensor 3 did give the highest reading. When a depth estimate was performed again, the result was still 40 ft. The sensor array was moved again toward the first clean out, which was the signal injection point for all of the tests. Once again, the depth estimate came back as 40 ft.

A simple amplitude locate was later performed with the sensors clustered on the floor of the hotel room, which is a slab on grade. There was no signal source connected; the data should have been the ambient noise seen by the sensors. For two repetitions of this test, sensors 3 and 5 gave higher signal levels than the other four sensors. The positions of sensors 3 and 5 were varied for these two trials to determine if position caused the elevated signal level. The result was that 3 and 5 were higher even when their positions were varied. This finding suggests that the sensor responses are not uniform. Given that the TOF estimate is based on a cross-correlation technique, the effects of sensor variations on the depth estimate should be minimal. As long as there is sufficient signal captured to maintain the shape of the chirp signal, a reasonable depth estimate should result.

The speculation at this point was that the convoluted pipe geometry at the first site was causing some distortion of the acoustic signal. The two vertical clean outs and multiple branches of the drain lines may generate echoes or resonances of the injected signal. Multiple signal paths to the sensors could blur the TOF findings and give erroneous depths.

A second test was performed at a site with a much simpler geometry near 1130 Talbotton Road. The site was a medical clinic set back roughly 40 ft from Talbotton Road. There is a parkway that is roughly 20 ft wide adjacent to Talbotton, a parking lot, and a small strip of grass adjacent to the building. The sanitary clean out was located in this strip of grass. The expected path of the pipe was from this clean out to a manhole located by the curb in the parkway; there were paint marks that supported this supposition.

The clean-out cover was removed and the speaker was mated with it (Figure 4.9). The opening was butted with the 3-in. fitting, which was the same size as the clean-out pipe. One of the rubber boots was used to provide a foot resting on the soil to stabilize the speaker. The site drawings provided by So-Deep Inc. indicated that the actual buried sanitary line was 6 in. in diameter.

The first sensor line was set up in the parking lot between the building and the parkway. The surface was new concrete in good condition. An amplitude locate shot was taken, and the indication was that the entire array needed to be moved slightly north. This was done, and another amplitude locate taken. This locate indicated the largest signal was at sensor 3. A few depth estimates were taken on the parking lot but with imprecise sensor spacing. All depths came back at 40 ft.

At this point the project team needed to move the array to accommodate a patient being picked up from the clinic. Because it was not possible to put the sensors back in their exact location, no more data were taken at this location.

The array was placed on the grass in the parkway adjacent to the clinic parking lot (Figure 4.10). This location was about 25 ft from the signal injection point. Several amplitude locates were done at this location to get the array centered. The array was repositioned laterally to adjust the spacing and location with respect to the expected location of the pipe. The distance from the parking lot curb was constant during these tests. The expectation was that this would provide a constant distance along the pipe being located from the signal source. All depth readings taken at this point came back at 40 ft.

Figure 4.10. Sensor line between clean out and manhole.

The view in Figure 4.11 was taken from the manhole near the curb of Talbotton Road. This was the expected terminus for the sanitary line being located as indicated by the site drawings. The signal injection source was to the right of the door and of the downspout seen on the medical clinic building. The initial set of readings was taken in the pavement behind the row of parked cars.

In every instance, the depth indicated from the TOF method was 40 ft. Given that this was clearly erroneous, no excavations were made on the basis of these data. No further acoustic data were taken in Columbus, Georgia.

The following actions were proposed for the acoustic prototype:

- Examine the data records collected at the second site for guidance about the issue with the TOF depth estimates.

Figure 4.9. Speaker on clean out near 1130 Talbotton.

Figure 4.11. View from manhole toward clean out.

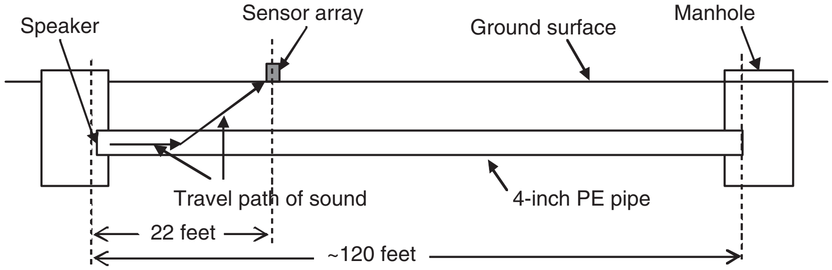


Figure 4.12. Acoustic testing on GTI pipe farm.

- Physically examine and test the six sensors to verify their proper operation.
- Test the system at a local site that replicates the geometry of the second site.
- Find another test site that provides a direct connection to a buried duct within a manhole, eliminating the bend and direction change of a clean out.

Follow-Up Testing of the Acoustic Locator

The results obtained during the in-service testing in Georgia were not as expected, and follow-up testing was required. After returning to GTI, the team made a series of measurements on a buried 4-in.-diameter polyethylene pipe. Figure 4.12 is a schematic of the test site. It provides a geometrically simple test situation of a straight pipe with no obstructions. Each end of the pipe terminates in a 4-ft diameter manhole, providing easy access to the open ends of the pipe.

Although the pipe is drawn straight, it has a gradual curve, with the low point near the middle. The total length of the pipe is approximately 120 ft. The sensor array was positioned 22 ft from the speaker and spaced equally across the pipe, with 2 ft between sensors. The right-hand end of the pipe is open to the atmosphere. Visual alignment placed the pipe location under sensor 3. Table 4.1 gives four sets of TOF data collected with this geometry. For the fourth set, the sensors were shifted by one spacing. Figure 4.13 plots the TOF values versus sensor position.

The graph shows a general trend, but there are several outliers that proved to be interference artifacts caused by multiple reflections. The outliers were removed and the data were combined into one set. The red (artifact) values in Table 4.1 were removed from the data set. A second-order polynomial regression was performed on the remaining data to obtain the equation of the best fit line for these data. Figure 4.14 plots the culled data set and the regression line. The regression line is at a minimum at sensor location 3.3, close to the location of the pipe.

The next step was to understand the cause of the outliers. Part of the data analysis was a correlation of the input signal driving the speaker with the waveform obtained/received/produced from each sensor. The input signal was a tone burst that started at a low frequency and continuously swept to a higher frequency. This process was selected to minimize the effects of sensor/soil coupling and background noises on the TOF values. The algorithm reported the arrival time as the time of the largest peak of the correlation.

Examination of the correlation waveforms showed multiple peaks of similar amplitudes were present rather than the single one expected. During the data collection, one of the researchers stood next to the far manhole while the burst pulse was fed into the speaker. A loud burst was heard, and it was followed by multiple reflections. The peaks in the correlation curves were

Table 4.1. Time-of-Flight (TOF) Data on GTI Pipe Farm

Sensor Position	Run 1	Run 2	Run 3	Run 4
1	**0.0698**	**0.0717**	1.1062	
2	0.0193	0.0212	0.0227	**0.0689**
3	**0.0727**	**0.0749**	1.7441	**0.0682**
4	**0.0654**	**0.0674**	**0.0688**	**0.0695**
5	**0.0655**	**0.0675**	**0.0688**	**0.0782**
6	**0.0721**	2.0651	**0.0755**	**0.0719**
7				**0.0730**

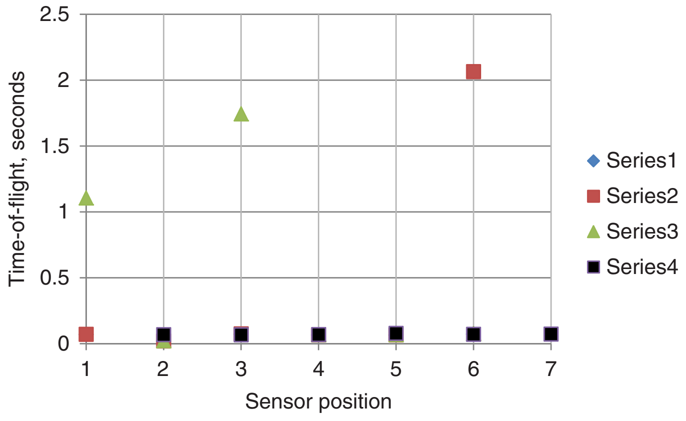


Figure 4.13. Acoustic TOF plots.

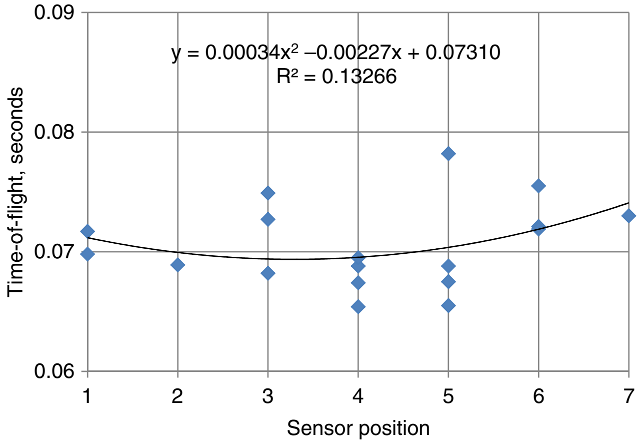


Figure 4.14. TOF data curve fit.

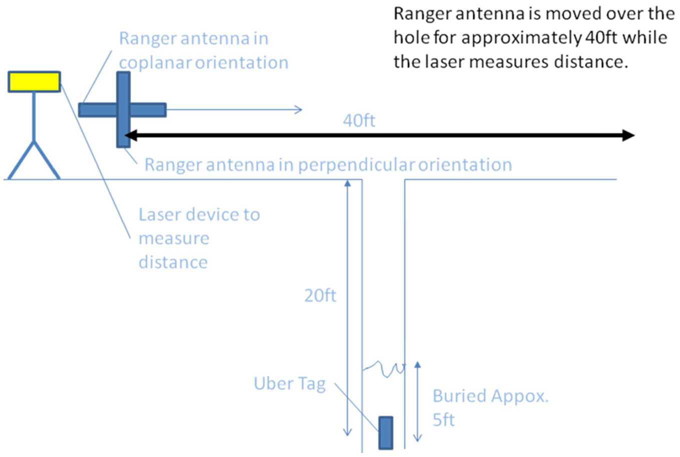


Figure 4.15. In-hole testing with laser range finder.

consistent with constructive interference of reflections from the two ends of the pipe. As a result, some of the correlation maximums of the reflections were larger than the correlation maximum occurring at the initial time of arrival, causing the algorithm to select the wrong maximum. Modification of the algorithm to select the first large peak should eliminate the outliers and improve the depth determination.

The sewer pipes in Georgia were also susceptible to multiple reflections and constructive interference. Examination of the correlation waveforms showed multiple peaks. The depth of the pipe was estimated using the TOFs from all six sensors and determining three unknowns. These unknowns were the following:

1. A term related to the velocity of sound in the soil;
2. The slope of the pipe; and
3. The depth of the pipe.

An equation that relates the terms is nonlinear; thus, an iteration process was used to obtain the values. The depth iteration process does not function if some of the TOF values are incorrect. Some reanalysis of the Georgia data was possible. The postanalysis numbers yielded a pipe depth of about 1.3 ft rather than the depth of greater than 40 ft obtained in Georgia. While the new value is better, a more accurate analysis of the data cannot be made. Maps of the Georgia sewer pipe show depths that range from 1 to 5 ft.

Long-Range RFID Tags

Preliminary Long-Range Tag Tests

This section describes the test setup and results from deep borehole testing of the VAI RuBee technology embodied in the prototype Uber long-range deep-burial tag. This testing was carried out in January 2011 near the VAI headquarters. The VAI RuBee tag can be detected underground at depths of 20 ft. The test was conducted as depicted in Figure 4.15.

VAI-supplied Finder software was used to record the signal strength of the tag as received by the base station. A laser device was used to accurately record the distance of the tag from the antenna during the testing. The VAI-supplied Ranger antenna and base station were initially placed 20 ft away from the borehole (ground surface). A vacuum-excavated hole was created with a depth of 20 ft, having an interior cavity of 1.5 ft by 1.5 ft. During measurements, the Ranger antenna was moved in a straight line toward the hole and continued past the hole to a location 20 ft from the hole on the opposite side.

The results of this testing can be seen in Figure 4.16 to Figure 4.19. These figures plot the signal strength of the tag and the location of the tag relative to the top of the hole. At a distance of zero, the base station antenna is approximately 20 ft away from the hole. At a distance of 20 ft, the base station antenna is directly above the hole. At a distance of 40 ft, the base station antenna is about 20 ft from the hole on the opposite side. The procedure effectively maps the signal of the tag relative to position.

The data from the Finder data logs were plotted as scatter plot and data point using color-coding of green and red data points. A green data point is a successful two-way tag ping (signal sent and acknowledged) using RuBee. A red data point is an unsuccessful ping (incomplete data transfer). The VAI base station receiver was optimized for multiple tag discovery whereby the average of multiple signal strength readings was required to obtain an absolute signal strength measurement, and this average value determined whether an acceptable or nonacceptable ping had taken place.

Figures 4.16 and 4.17 show the signal strength of the tag placed 20 ft into an open hole. In Figure 4.16, the base

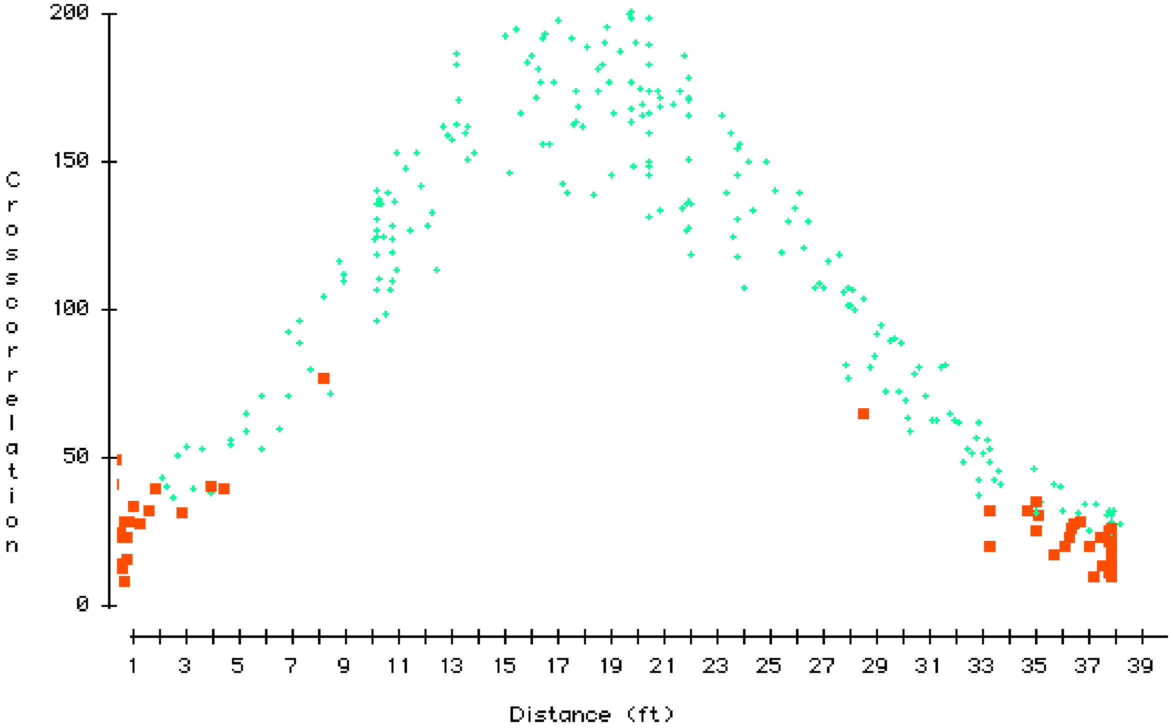


Figure 4.16. Uber Tag at 20-ft depth with no cover. The base station has a Ranger antenna in a coplanar (parallel) orientation. Green indicates that the tag was read correctly. Red indicates that there was an error in reading the tag data.

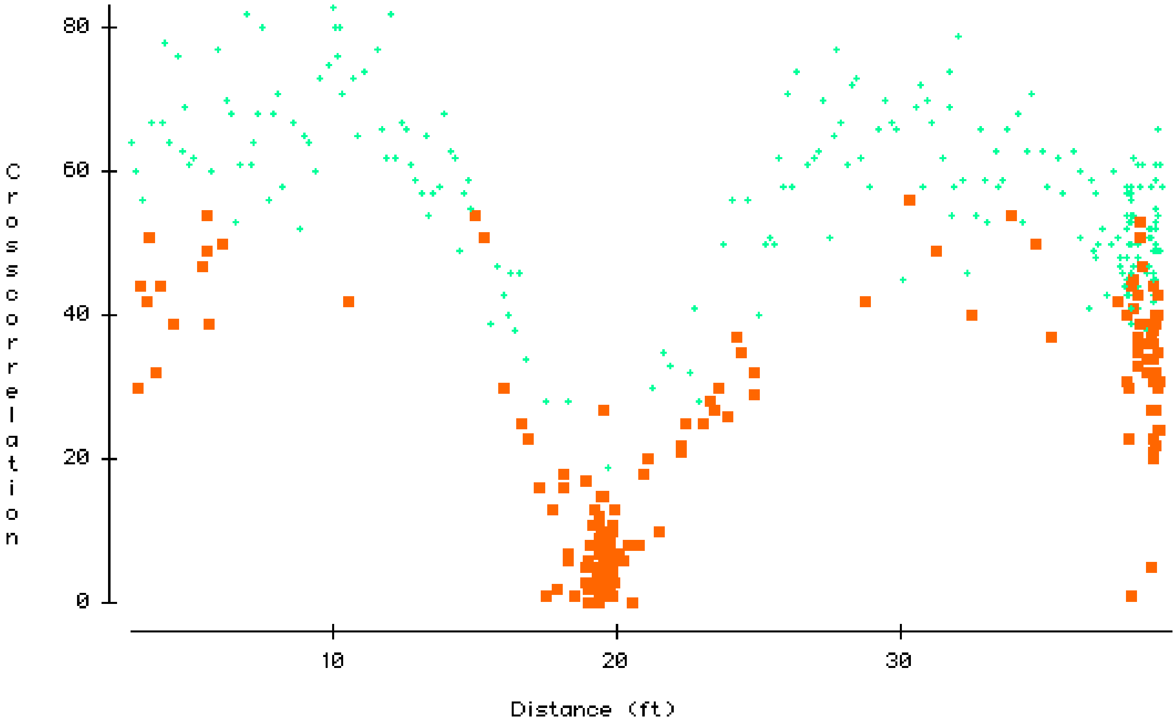


Figure 4.17. Uber Tag at 20-ft depth with no cover. The base station has a Ranger antenna in a perpendicular orientation. Green indicates that the tag was read correctly. Red indicates that there was an error in reading the tag data.

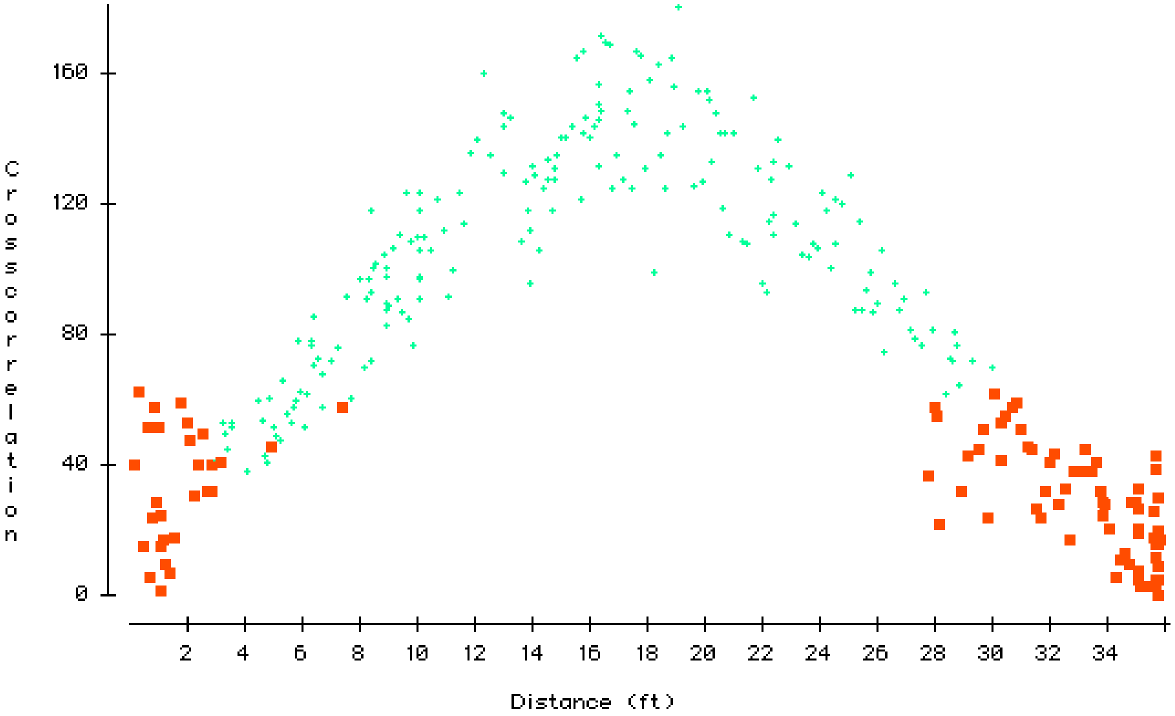


Figure 4.18. Uber Tag at 20-ft depth with 5-ft soil cover. The base station has a Ranger antenna in a coplanar (parallel) orientation. Green indicates the tag was read correctly. Red indicates that there was an error in reading the tag data.

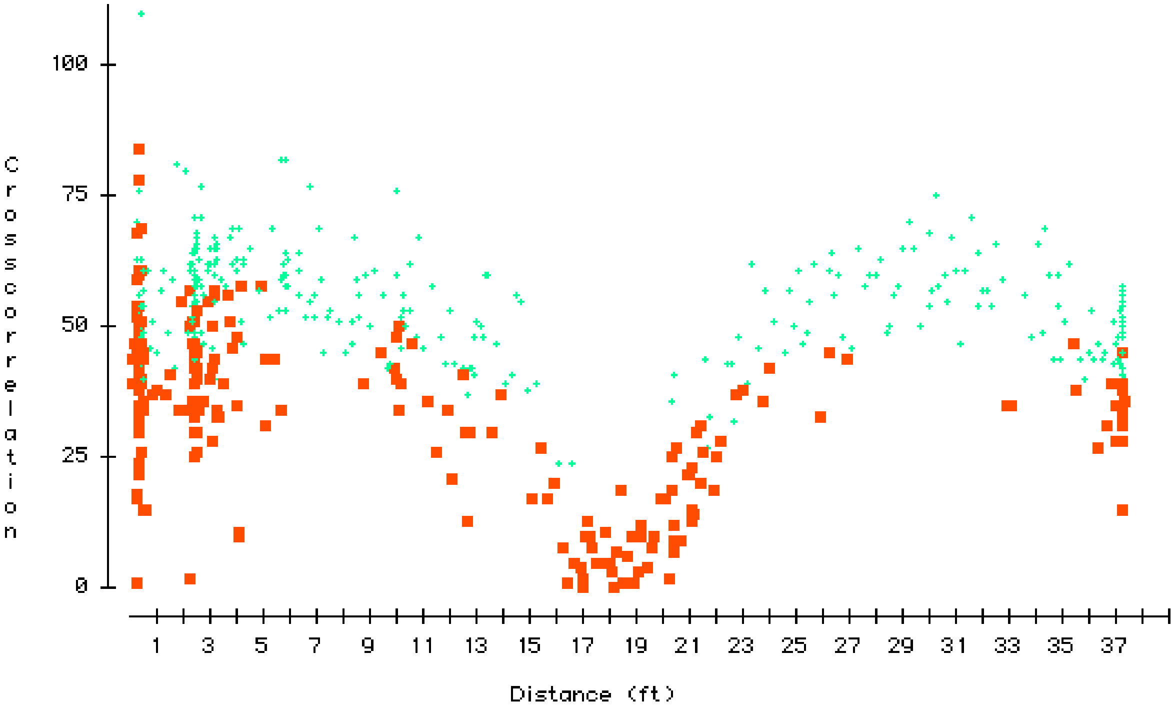


Figure 4.19. Uber Tag at 20-ft depth with 5-ft soil cover. The base station has a Ranger antenna in a perpendicular orientation. Green indicates the tag was read correctly. Red indicates that there was an error in reading the tag data.

station antenna is in a coplanar orientation (see Figure 4.15). This antenna orientation is the best orientation to receive maximum signal strength from the tag, and the peak signal strength occurs when the antenna is directly above the tag. In this orientation (as shown in Figure 4.16), the tag can be detected within a 17-ft radius around the hole. The signal strength increases and peaks at 19 to 20 ft, around where the hole was located. Figure 4.17 shows the signal strength with the antenna in the vertical orientation (see Figure 4.15.). Although less signal strength is measured in this orientation, this orientation gives one the best indications of where the tag is specifically located. Figure 4.17 shows that the signal strength of the tag falls out at around a 19-ft radius from the hole.

The results of Figures 4.18 and 4.19 show the tag under the same conditions as Figures 4.16 and 4.17, except that the tag was buried with 5 ft of soil cover. In the coplanar orientation (Figure 4.18), a noticeable loss of about 20% of signal strength can be observed. This also lowered the detection radius from 17 ft to about 12 ft. Even with this loss of signal strength, Figures 4.18 and 4.19 pinpoint the tag to about 18.5 ft, which is around the borehole area.

The conclusions that can be drawn from the borehole testing are promising. The Uber Tag is easily detectable 20 ft in the ground within a radius of 10 ft from the center point both before and after backfill. There was a reduction in signal strength when the tag was buried with 5 ft of soil cover; however, the detection radius remained as good as any existing commercial product while being far superior in depth.

The following are probable causes for this reduction:

1. Soil detuned the tag.
2. The tag generated eddy currents in the soil.
3. Soil inhibited the magnetic field of the tag, thereby changing the strength of the field.

If the signal strength reduction is the result of causes 1 and 2, then the effect of soil on the tags is only a localized phenomenon and no effect should be seen, even if the 20-ft hole the tag is in is completely backfilled. If cause 3 is the reason for the signal strength reduction, then backfilling the hole completely may lead to further signal degradation. Given that the tag's magnetic field is able to penetrate the soil when the base station antenna is 20 ft away (surface distance) from the borehole opening, meaning the soil distance is 28 ft, cause 3 is not likely.

Figures 4.15 through 4.19 highlight how easily the position of a properly oriented tag in the ground can be detected by a handheld device using both coplanar and perpendicular antenna orientations. In conclusion, the RuBee Uber Tag is readily detectable when buried at 20 ft.

In-Service Testing of Long-Range Tags

There are some general observations about the test site in Georgia: there are no truly deep utilities within the Talbotton Road project, and the frost line in the region is such that it is difficult to find much in excess of 6 ft deep. Only one location was set up with two stacked utilities; a total of four tags were installed at the Columbus site.

There were several issues with the portable RuBee tag locator, the V-Rod (Figure 4.20). The startup of the V-Rod was erratic, often requiring several resets to achieve stable operation. Once activated properly, the V-Rod did provide a reasonable method for locating and identifying individual tags; it can be used in both a peak and null mode to center the location of a buried tag. It does identify all the tags in the immediate vicinity and then allows the operator to select one from the list to perform locating. There are several ergonomic issues that need improvement with the V-Rod. The weight/center of gravity needs to be adjusted such that the antenna is closer to the ground, as with current EM instruments. This would improve the handling and also increase the signal strength by decreasing the distance to the tag. The display graphics could be improved, but a more important step would be to provide a louder audible indicator of signal strength. The current "Geiger counter click" is too soft for traffic conditions. As a result, the operator has to spend a lot of time looking at the display.

The physical packaging of the tags for field installation will require some improvement. The prototypes are cemented with RTV, but the production devices will need to be ultrasonically welded. The tags are cylindrical and provide the strongest signal when their long axis is aligned with that of the reading antenna. For a very deep installation, the optimum orientation is with the tag standing on end. This was accomplished during the field test by attaching the tags to warning marker tape and lowering them into the excavation to the appropriate depth. Maintaining the upright orientation

Figure 4.20. V-Rod portable locator and tags.

Location	Tag ID	Tag Type	Tag Depth (ft)	Signal Strength
2039 Warm Springs Road	770020	Uber	5.25	2300
2039 Warm Springs Road	660000	Asset	4.50	1125
1801 Warm Springs Road	660004	Asset	5.75	400
29th and Talbotton Road	660002	Asset	5.00	670

Figure 4.21. Signal strengths versus depth for the Columbus RuBee tags.

during backfill requires care. Even a small tilt can throw off location by several feet if the tag is at a 20-ft depth. A self-leveling package, such as the 3M marker ball, would be advantageous. Given the range of the Uber Tags, it would also be possible to install the tags parallel to the buried facility. This would allow an operator to both locate the facility and determine its run direction from aboveground.

There was significant scatter in the signal strength from the various tags. Two types of tags were provided for this field test: the long-range Uber Tag and the medium-range Large Asset Tag. VAI claims that the variation would be significantly reduced in production devices. Several of the Uber Tags have been returned to VAI for testing to verify how much the signal strength has drifted since they were fabricated.

Figure 4.21 shows signal strengths for the various tags buried in Columbus. The strengths are given in arbitrary units and a minimum level of 50 is required for the tag to be detected and read. The readings were taken with the V-Rod receive antenna located at about chest height for the operator. The distance from the ground to the location of the V-Rod must be added to the burial depth given in the table. There is still a good deal of scatter, even when adjusted for distance, in the signal strength of the Large Asset Tag, which is a production item for VAI.

The longer-range Blaster tag reader, shown in Figure 4.22, was also tested briefly. This device has a greater range and a more elaborate data display than is provided using a laptop. This device would be appropriate for mounting on a mobile platform, such as a car or survey radar cart. The system has three components: an antenna, the base station, and an attached PC to run the display software. The Blaster can quickly identify tags over a large area. With the appropriate choice of antenna, it could also be used to locate tags. The rod-style antenna is less affected than the open-loop antenna by the presence of nearby metal. The rod-style antenna is therefore a better candidate for mounting on a vehicle bumper or trailer hitch to allow tag surveys to be conducted from a moving vehicle.

The following were action items with respect to the long-range RFID tags:

- Find locations for deeper burial of the remaining tags.
- Make improvements to the V-Rod firmware to improve user interface and reliability.
- Determine the cause and remedy for the scatter in the signal strengths of the tags.
- Improve physical packaging to deal with alignment and sealing issues.

Two tags were buried near 2039 Warm Springs Road just west of Calvin Drive in Columbus. An Uber Tag was located on a 10-ft clay sanitary line at a depth of 5.25 ft, and an Asset Tag was located on a telecom duct at a depth of 4.5 ft. Both could be identified and located after the backfill and paving were applied. Figure 4.23 shows the V-Rod being used in the null mode, with the antenna orthogonal to the tag, to precisely center the lower tag. Both tags were located under the patch visible in the pavement.

A third tag was installed on a six-way RPC duct near 1801 Warm Springs Road. This device was a Large Asset Tag. Once again, it was readily locatable after the backfill and patch was

Figure 4.22. Base station tag reader with two alternative antennas.

Figure 4.23. Using V-Rod to locate two tags buried near 2039 Warm Springs Road.

Figure 4.25. Fourth tag was buried at 29th Street and Talbotton Road.

applied. In Figure 4.24, the V-Rod is being used in the peak mode, with the antenna parallel to the tag, to identify and locate the tag.

The fourth tag was installed at the bottom edge of a telephone duct located at the intersection of 29th Street and Talbotton Road (Figure 4.25). As with the other installations, the duct was exposed using vacuum-excavation techniques. The duct is a rectangular, concrete structure that runs in the south margin of Talbotton Road. The tag was readily located after the excavation had been backfilled.

Figure 4.24. Third tag was buried near 1801 Warm Springs Road.

Another excavation was started but was not completed during the field-test period. This was another telephone duct that was discovered to be located in a wet clay soil. The nature of the soil slowed the vacuum excavation. Given that this would only have given a depth of 7 ft when exposed, the team elected to reserve the Uber Tags for deeper locations that might appear during the course of the Talbotton Road project.

Additional Testing of Long-Range RFID

Additional testing had been planned using a 20-ft-deep borehole on the GTI campus. Two improved versions of the Uber Tag were provided to GTI but did not arrive until late in December 2012. One-Call clearing the site and acquiring a contractor to perform the bore were not possible at that late date. The improved Uber Tags were tested in free air and found to have a range in excess of 40 ft. Given the frequency of operation, 131 kHz, the overburden of 20 ft of soil would have little effect on the signal strength. This statement is supported by the results of borehole testing that was performed in the Toronto area. The extended range of these tags meets the original goal: they can be placed on a utility at a depth of 20 ft and still have sufficient range margin to be locatable over a wide area at the surface.

CHAPTER 5

Conclusions and Recommendations

A broad range of potential technological improvements for utility locating and characterization were identified in the SHRP 2 R01 study, Encouraging Innovation in Locating and Characterizing Underground Utilities. These were then evaluated with respect to SHRP 2's expected time and funding constraints and the program's desire for short- to mid-term results with minimal duplication of the activities under way at other organizations. One area selected for further research and development was a solution for locating deep and stacked utilities.

Five areas for research and development were selected after a literature search was performed to identify promising geophysical and tagging solutions for the deep and stacked problem. Prototype development was initiated in all five areas. Development was downselected to two technologies on the basis of bench testing or early field testing. The scanning electromagnetic locator was abandoned after bench trials showed significant technological barriers that could not be overcome within budget and time. The work on internal inertial mapping systems was halted because this is a proven, if expensive, technology rather than an area of research. The seismic platform was put on hold after meeting significant but not thought to be insurmountable problems.

The remaining two areas, a long-range RFID tag and an active acoustic locator, were developed to the prototype stage and field-tested. Both technologies need more development to bring them to a commercial-ready state. At this time the RFID tag, suitable for utilities at a 20-ft depth, is the technology closest to commercial readiness. The remaining issues for the RFID technology are packaging and ergonomics for field use.

A finding that was common to both the seismic reflection and the active acoustic technologies is that the propagation of mechanical vibrations in soil is extremely sensitive to coupling. This may be the coupling of the signal emitter to the soil or the vibration sensor to the soil. Significant effort will be required to normalize or calibrate the soil-to-device interface. This line of inquiry will not be fruitful until the coupling issue can be handled in a repeatable fashion.

At present, there is no prospect that an aboveground tool will be developed in the foreseeable future that can simply and quickly locate a majority of deep or stacked buried utilities at a site. In truth, there is little likelihood that such a tool could ever be developed because of site geometrics, differing soil conditions, and limitations in power and frequency.

APPENDIX A

Subsurface Utility Engineering Quality Levels

Highway plans typically contain disclaimers about the quality of utility information. The use of quality levels in the Subsurface Utility Engineering (SUE) process allows designers to certify on the plans that a certain level of accuracy and comprehensiveness has been provided. There are four quality levels:

- *Quality Level D* information comes solely from existing utility records. It may provide an overall feel for the congestion of utilities, but it is often highly limited in terms of comprehensiveness and accuracy. Its usefulness should be confined to project planning and route selection activities.
- *Quality Level C* involves surveying visible aboveground utility facilities, such as manholes, valve boxes, and posts, and correlating this information with existing utility records. When using this information, it is not unusual to find that many underground utilities have been either omitted or erroneously plotted. Its usefulness, therefore, should be confined to rural projects where utilities are not prevalent or are not too expensive to repair or relocate.
- *Quality Level B* involves the use of surface geophysical techniques to determine the existence and horizontal position of underground utilities. This activity is called "designating." Two-dimensional mapping information is obtained. This information is usually sufficient to accomplish preliminary engineering goals. Decisions can be made on where to place storm drainage systems, footers, foundations, and other design features to avoid conflicts with existing utilities. Slight adjustments in the design can produce substantial cost savings by eliminating utility relocations.
- *Quality Level A* involves the use of nondestructive digging equipment at critical points to determine the precise horizontal and vertical position of underground utilities, as well as the type, size, condition, material, and other characteristics. This activity is called "locating." It is the highest level presently available. When surveyed and mapped, precise plan and profile information is available for use in making final design decisions. By knowing exactly where a utility is positioned in three dimensions, the designer can often make small adjustments in elevations or horizontal locations and avoid the need to relocate utilities. Additional information, such as utility material, condition, size, soil contamination, and paving thickness, also assists the designer and utility owner in their decisions.

The end product (the CADD file or project plans) may contain any or all of these quality levels.

APPENDIX B

Combined Technical Assessment of SHRP 2 Projects R01B and R01C

Executive Summary

The objective of this project is to design, construct, and test prototype instruments for locating buried utilities. These prototypes will be based on new and emerging technologies. The first step is the review of existing and promising technologies for location and tracing of buried infrastructure as applied to deeply buried pipe. This review is intended to ensure that this project does not repeat previous efforts, to verify the need for new location tools, to define operating needs of the industry, to provide the stakeholders information to accurately assess emerging technologies, and to provide confidence that the proposed methods can succeed.

A number of comprehensive technology reviews have recently been completed (*1, 2, 3*). These reviews cover existing, emerging, and conceptual ideas for utility location technologies. SHRP 2 Report S2-R01-RW is especially comprehensive, reviewing the literature with more than 350 references (*1*). SHRP 2 R01A also reviewed locating technology. The Gas Technology Institute (GTI) performed a study for a number of natural-gas utilities that tested commercially available pipe location techniques (*4*). Part of that study also evaluated emerging technology. All the studies identify the same technologies that are promising but require near-term development. One conclusion reached in all the studies is that no single tool can function well in all soil conditions. For example, ground-penetrating radar (GPR) is good in dry, nonconducting soil, but it cannot detect utilities more than 3 to 4 ft deep in wet clay. Therefore a range of complementary techniques is required. These could be combined into a single system or applied as individual tools.

The ability to assess the new technologies and understand how they complement each other requires understanding soil properties and wave propagation. This appendix summarizes the key electromagnetic and acoustic wave properties and soil properties with the goal of providing understanding of why various technologies function well in some soils and not in others. This information permits assessment of technologies in terms of the ultimate depth location. Next, the operating principles behind the commercially available and most promising technologies are described, including their strengths and weaknesses. A brief description of how the new technologies will improve deep utility location is given.

Analysis of this information justifies development of seismic, active acoustic, smart tag, inertial guidance system, and electromagnetic (EM) technologies as applied to deeply buried utilities.

Introduction

This appendix reviews existing and promising technologies for location and tracing of buried infrastructure as applied to buried utilities. Ideally, a tool would be able to locate and identify a buried utility without making a connection to the pipe and only knowing its general position. GPR can do this for a limited set of soil conditions. However, the most commonly used tool, an electromagnetic pipe locator, requires knowing the location of the pipe at one position, injecting a signal on the pipe, and tracing the path of the pipe. Because practical tools are needed, both approaches are acceptable.

Other than excavation, there are six general approaches for determining the location of buried facilities:

1. Inserting and moving a tool inside the pipe that can keep track of its position relative to the entry point. An example is an inertial navigation system (INS) with GPS.
2. Placing an identification tag in or near the utility that can be read from aboveground. An example is a smart tag.
3. Creating a wave/signal inside the utility with propagation to the surface for detection. Examples include electromagnetic pipe and active acoustic locators.
4. Generating a wave/signal at the surface of the ground, propagating it to the utility, interacting with the utility,

and returning to the surface. Examples include GPR and seismic reflection location.

5. Creating acoustic, electromagnetic, or GPR signals close to the pipe with detection at the surface.
6. Measuring slight differences in the earth's magnetic or gravitational field. Potential field (passive) techniques include magnetic methods and gravity gradient methods. Fundamentally, these methods rely on existing natural earth fields, either magnetic or gravitational, to ascertain differences in subsurface materials.

This appendix examines the following: GPR; EM tracing of metallic utilities; magnetic locators; time-domain electromagnetic induction (TDEMI); seismic reflection location; active and passive acoustic location; INSs; smart tagging; infrared thermography; and capacitive tomography.

Approaches 2 through 5 require propagation of an EM or acoustic wave through the overburden. EM and acoustic waves of various frequencies are options that have been developed, and improved versions are proposed in this project. An understanding of the limitations of current technology for locating buried utilities and the rationale for the improved utility location techniques proposed in this project requires a general knowledge of how soil properties affect the locating technologies. It also requires an understanding of the ability of waves to "see" objects. The large range of soil properties also explains the need to have an arsenal of complementary techniques. The adsorption of both acoustic and electromagnetic waves in soil is a complex function of frequency, soil properties, and the physics of waves. The description presented here simplifies the subject with the goal of providing a general understanding in a limited space. It starts with plane waves. A brief summary of the effects of geometric spreading, source directivity, and scattering effects follows the plane wave discussion.

Before delving into the physics, a summary is given on the limits of existing and emerging technologies for locating utilities and the advantages of the proposed technologies.

Summary of the Findings and Conclusions of the Technical Discussion

This section summarizes the key findings and conclusions of the technical discussion.

- Some pipe location technologies (EM, GPR, and smart tags) involve propagation of electromagnetic radiation through the overburden. These location signals are subject to attenuation caused by soil properties. The controlling properties are the frequency of the waves and the electrical conductivity, relative dielectric constant, and relative magnetic permeability of the soil. Relative dielectric constant is a strong function of water content of the soil. Electrical conductivity depends on mineral, salt, and water content of the soil. Dry, sandy soils have relatively low attenuation. Wet clay soils are highly attenuating.
- Similarly, some pipe location technologies involve the propagation of acoustic signals. There are two types of acoustic waves: shear and longitudinal. The acoustic location signals are subject to attenuation caused by a different set of soil properties. In general, the attenuation of soil decreases as water content increases.
- Attenuation increases exponentially with the frequency of the waves. This is true for both EM and acoustic waves. Greater depth penetration is achieved with lower frequencies (i.e., longer wavelengths).
- GPR and seismic reflection location detect the pipe by reflecting waves from the pipe's surface. The fundamental nature of waves places a limit on the wavelength used to see a cylindrical object/pipe with reflected radiation. If the wavelength is an order of magnitude or more smaller, the object acts as a mirror. If the frequency is too low, the wavelength is too long, and the wave passes by the cylinder with little reflection. The transition between the two occurs when the wavelength equals the circumference of the pipe. For example, a frequency of approximately 200 MHz or greater is required to detect a 6-in.-diameter pipe with GPR.
- This wavelength limit does not apply to location techniques in which the pipe radiates a signal, including electromagnetic locators and active acoustic techniques.
- GPR is strongly affected by soil properties. In dry, sandy soils, GPR works well for finding buried utilities. However, for wet and clay soils, the waves attenuate rapidly. At the frequencies required to detect a 6-in. pipe with GPR, depth of detection is less than 4 ft. Research in improved signal processing, antenna design, and greater power in the pulse signal is extending the depth range; however, the exponential nature of attenuation and the high attenuation constants in clay/high moisture soils is too strong to overcome for deeply buried pipe. An additional technique is needed for such soils.
- EM locators are strongly affected by soil properties. The requirements to couple current into the pipe and have a return path through the soil make it difficult to make general comments on the detection depth. Field experience reported by natural-gas utilities has found that for most soils the practical maximum range of electromagnetic locators is 10 ft.
- An array of complementary pipe location tools is required to handle all the pipe and soil types. There are also potential synergies between the proposed techniques that can be exploited.

General Background on Physics of Detection

Almost all subsurface measurements fall into four basic categories:

1. *Electromagnetic.* This category includes light, radio waves (radar), and the low-frequency (quasi-static) EM fields, and attendant eddy current induction in conducting materials, throughout the electromagnetic frequency spectrum.
2. *Acoustic.* This category includes sonar and seismic waves, which include reflection and refraction measurements. Further, the seismic methods can be broken into compressional (P) and shear (S) waves. S-waves have particle motions polarized transverse to their direction of propagation.
3. *Electrical.* This category includes methods that use the introduction of alternating current (AC) or direct current (DC) into the earth or the application of AC or DC voltages to the earth to measure variations in conductivity (or resistivity) or permittivity. The resistivity method is the principal method used. A variation on the electric field method is one in which an AC current is impressed on a subsurface metallic pipe, and the resulting magnetic field is tracked from the surface.
4. *Potential field.* This category includes the magnetic method and the gravity and gravity gradient methods. Fundamentally, these passive methods rely on existing natural earth fields, either magnetic or gravitational, to ascertain differences in subsurface materials.

Of these methods, GPR and EM conductivity methods have been the most successful with respect to utility location. GPR has excellent resolution and is capable of locating objects as small as 1 in. in diameter. EM conductivity has reasonable resolution, but it is only responsive to metallic or other conductive objects in the subsurface.

These two methods have different but equally critical limitations. EM measurements can penetrate into conductive soils. However they do not have the resolution to detect small objects at depths greater than about 5 ft away from the EM source and sensing coils.

GPR cannot penetrate more than a few feet in highly conductive soils. This is because the conductive soil medium tends to attenuate the propagating electromagnetic signal to the point that reflections are too weak to be detected upon returning to the surface. This is analogous to using the headlights of a car to detect objects ahead of the car in a dense fog. The water particles in the fog tend to scatter and diffuse the light beams from the headlamps, preventing any useful illumination of objects more than a few feet from the headlights.

Acoustic and seismic methods have been used to a limited degree for utility detection. Principally, those methods that rely on reflected energy, directly analogous to sonar techniques, have been used for utility detection. Reflection techniques can be subdivided into two categories:

- Techniques using P-waves; and
- Techniques using S-waves—in particular, using S-waves that have particle motions polarized parallel to the ground surface (SH-waves).

Passive potential field methods have not been used for utility detection, because they do not provide the required resolution for utility detection. Resistivity methods have not been used, because they also lack resolution in cluttered environments and are somewhat difficult to implement in the field.

An additional area of technology has become available for making subsurface measurements. Field systems that use nuclear magnetic resonance (NMR) have been in use for a few years, and newer ones have more capability. NMR employs a nuclear spin technology that is similar to electromagnetics in that EM fields are generated, but the nuclear aspect allows the system to be targeted at certain materials. Currently available systems have been developed to find water resources 500 to 1,500 ft below the surface. These systems essentially perform a magnetic resonance imaging (MRI) scan of the subsurface, but the sources and receivers cannot be on all sides of the area to be imaged, as with the MRI scanner used in medical applications. There is a chance that newer systems will be adaptable for utility mapping, but the area of application would be limited to pipes containing water. Table B.1 lists potential technologies to detect and map utilities.

Wave Propagation and Soil Properties

This section addresses electromagnetic and acoustic wave propagation in soils and the range of soil properties affecting propagation, attenuation, and the ability to detect buried objects.

Plane Wave Attenuation

As waves propagate, their amplitude is affected by two factors: adsorption of energy by the soil and geometric spreading of the wave. The adsorption portion or attenuation of both acoustic and electromagnetic waves has the following general form:

$$A = A_o \exp(-\beta x) \tag{B.1}$$

where

A_o = the initial amplitude of the wave,
β = attenuation coefficient for a specific frequency and soil, and
x = the distance traveled in the soil.

This necessitates a discussion of electromagnetic and acoustic soil properties.

Table B.1. Potential Technologies to Detect and Map Utilities

Technique	Utility Material	Property Measured	Soil Type	Detection Limit	Critical Property	Development Needed	State of Development
Acoustic holography	Any	Seismic velocity or attenuation	Any	Approximately 30 ft or less	Seismic velocity or attenuation contrast	High	Low
Active EM detection	Conductive	Radiated EM signal	Any	Less than 50 ft	Radiated field strength—imposed on line	Available now	NA
Frequency-domain EM	Generally conductive	Induced EM field	Nonconductive	Less than 10 ft	Conductivity contrast	Available now	NA
Capacitive EM	Any	Low-frequency EM	Any	Less than 20 ft	Dielectric contrast	Moderate	Low
Gas detection—chemical	Gas filled or containing volatile	Concentration	Any	Less than 50 ft	Gas or contaminant concentration	Moderate	Low
Ground-penetrating radar	All	Reflected EM field	Nonconductive	Less than 30 ft	Conductivity/permittivity contrast	Available, but modifications in progress	High
Induced polarization	Conductive	Electrical potential	Any	Approximately 30 ft	Conductivity contrast	High	Low
Infrared thermometry	Any	Temperature	Any	Approximately 10 ft	Temperature contrast	Available	NA
Leak detector	Fluid filled	Sound	Any	Less than 20 ft—leak-size-dependent	Radiated pressure field	Available in several forms	NA
Magnetic field	Magnetic	Magnetic permeability	Nonmagnetic	Less than 25 ft	Magnetic susceptibility contrast	Available	NA
Metal detector	Conductive	Induced EM field	Relatively nonconductive	Less than 25 ft	Conductivity contrast	Available	NA
Nuclear magnetic resonance	Contains polar molecules	Spin resonance	Relatively dry	Unknown	Variations in water content	Moderate to high	Existing systems are used on very large targets.
Passive EM detection	Conductive	Radiated EM field	Any	Signal-strength dependent, typically less than 15 ft	Radiated field strength	Available	NA
Pressure waves	Fluid filled	Pressure or acoustic wave	Any	Rated to 500 ft	Radiated pressure field	Available	NA
Resistivity	Any	Current/resistivity	Relatively nonconductive	Approximately 30 ft	Conductivity contrast	Available	NA
Seismic reflection	Any	Seismic velocity	Any	Approximately 30 ft or less	Seismic impedance contrast	Moderate to high	Needs to be done at higher frequencies.

(continued on next page)

Table B.1. Potential Technologies to Detect and Map Utilities (continued)

Technique	Utility Material	Property Measured	Soil Type	Detection Limit	Critical Property	Development Needed	State of Development
Seismic refraction	Large diameter	Seismic velocity	Any	Approximately 30 ft or less	Seismic impedance contrast	Available but not for utility mapping	High
Seismic tomography	Size dependent	Seismic velocity or attenuation	Any	Approximately 30 ft or less	Seismic velocity or attenuation contrast	Available but not for utility mapping	High
Spontaneous potential	Conductive	Electrical potential	Any	Approximately 30 ft	Conductivity contrast	Available but not used for utilities	Moderate
Sonic	Hollow pipe	Sound	Any	Less than 50 ft	Radiated pressure field	Under development by Mapping the Underworld (MTU)	Low to medium
Sonic and subsonic acoustics	Any, preferentially large diameter	Seismic impedance or scattering	Any	Less than 150 ft	Acoustic impedance contrast	High	Low
Spectral analysis of surface waves (SASW)	Any	Ground motion	Any	Less than 30 ft	Seismic velocity contrast	Available but not used for utilities	Moderate
Time-domain EM	Generally conductive	Induced EM field	Nonconductive	Less than 10 ft	Conductivity contrast	Available and improvements possible	Low to moderate
Ultrasonic acoustics	All	Acoustic impedance	Any	Less than 10 ft	Acoustic impedance contrast	High	Low

Note: NA = not available.

Electromagnetic Properties of Soils

Electromagnetic wave propagation in soil is governed by Maxwell's equations. These equations can be solved in one dimension for a wave propagating into a conducting medium (*5, 6*). The key properties are electrical conductivity (σ), the dielectric permittivity (ε), and the magnetic permeability (μ). In soil, σ and ε are strong functions of the frequency of the wave and the water content of the soil. Historically, it has been easier to compare materials by expressing the relative magnetic permeability and relative dielectric constants as a ratio referenced to the values in vacuum. The magnetic permeability, μ, is given as the following:

$$\mu = \mu_r \mu_o \tag{B.2}$$

where

μ_r = the relative permeability, and
μ_o = permeability of vacuum = 1.26×10^{-6} Henry/m.

The relative magnetic permeability of vacuum is exactly 1.00. For practical purposes, the values for air and natural gas can be considered as 1.0. Most soils do not have iron or magnetic content, thus their relative magnetic permeability is also close to 1.0. Similarly, the dielectric permittivity is given as the following:

$$\varepsilon = \varepsilon_r \varepsilon_o \tag{B.3}$$

where

ε_r = the relative dielectric constant, and
ε_o = the permittivity of vacuum = 8.854×10^{-12} Farads/m.

The relative dielectric permittivity of vacuum is exactly 1.00. The values for air and natural gas can be considered as 1.00. Table B.2 lists relative dielectric constants for some materials.

The relative dielectric constant, ε_r, of a soil is a complicated function. Water content is an important factor. Examples of the ranges of relative dielectric constant, the conductivity of soils, and their dependence on moisture content were obtained as part of the development of a GPR unit for locating natural-gas pipes (*7*). Data on relative dielectric constant, soil conductivity, and volumetric moisture content were collected at 131 sites in California, New York, Ohio, and Texas. The relative dielectric data versus moisture content by volume was combined with seven studies by other researchers. Analysis of the data showed that all the values fell in a fairly narrow band and could be represented by a third-order polynomial regression equation. The researchers concluded that there is a strong correlation between the relative dielectric constant of the soil and volumetric water content and only a weak correlation with soil type, density, temperature, and salt content. This conclusion was applied for frequencies between 20 MHz and 1,000 MHz. Figure B.1 shows

Table B.2. Relative Dielectric Constants and Electromagnetic Velocities

Material	ε_r, unitless	VM, mm/ns
Air	1	300
Water	81	33
Polar snow	1.4–3	194–252
Freshwater ice	4	150
Permafrost	1–8	106–300
Coast sand (dry)	10	95
Sand (dry)	3–6	120–170
Sand (wet)	25–30	55–60
Silt (wet)	10	95
Clay (wet)	8–15	86–110
Clay soil (dry)	3	173
Average "soil"	16	75
Granite/basalt/shale	5–9	106–120
Concrete	6–30	55–112
Asphalt	3–5	134–173
PVC/PE	3	173

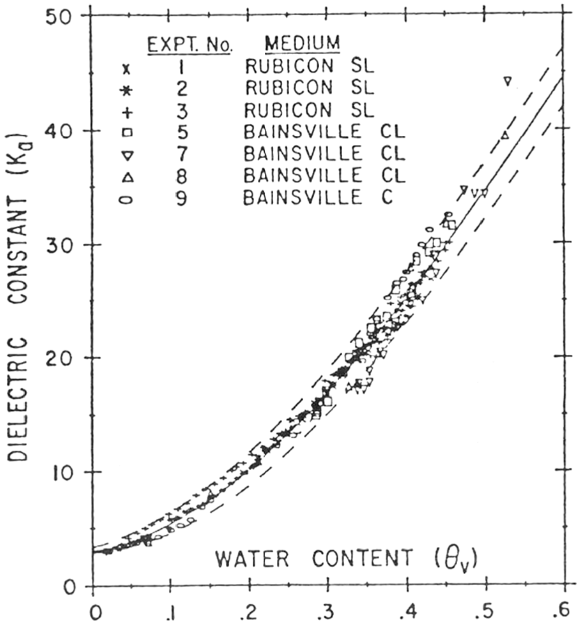


Figure B.1. Combination of data relating measured volumetric water content to relative dielectric constant.

a superposition of the regression equation. Rough estimates for ε_r can be made from the following general values for moisture content in soil. Percent moisture by volume and the corresponding moisture content by percent weight for a few soils are shown in Table B.3. Thus, the range of water content plotted in Figure B.1 spans from 0% to 53% water by volume. The relative dielectric constant varies from 4 to 50.

Table B.3. Moisture Content of Soils

Material	% Water by Volume	% Water by Weight
Dry sand	1%	—
Saturated sand	44%–52%	25%–30%
Saturated clay	77%	25%–30%

The study also looked for a relationship between relative dielectric constant and conductivity for the 131 sites. Figure B.2 is a plot of the conductivity of a soil versus its dielectric constant. The data show that there is a general relationship between relative dielectric constant and electrical conductivity. As the relative dielectric constant increases because of increasing soil moisture content, the electrical conductivity also increases, but at a faster rate. Values for the relative dielectric constant ranged from 4 to 50. Values for the electrical conductivity ranged from 4 to 300 millimhos per meter. The scatter in the relationship is due to the fact that the soil electrical conductivity depends on the salt content of the soil as well as the water content. All measurements were taken at 40 MHz. The study also observed that electrical conductivity increases with frequency.

As mentioned above, Maxwell's equations can be solved for waves propagating in a conducting medium. The results include Equation B.4 for the velocity of the waves and Equation B.5 for the attenuation coefficient of the waves.

$$V_m = c(\varepsilon_r \mu_r/2)^{0.5} \left\{ \left[1+(\sigma/2\pi f\varepsilon)^2\right]^{0.5} - 1 \right\}^{-0.5} \qquad \text{(B.4)}$$

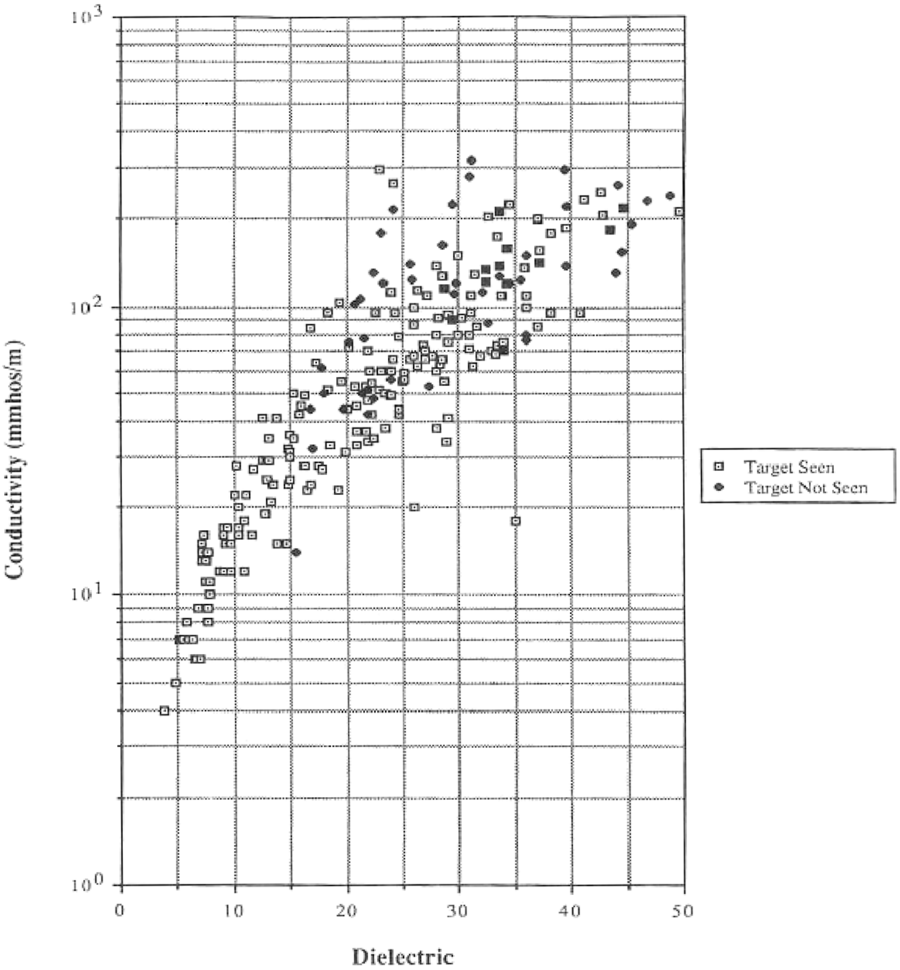


Figure B.2. Data from 131 sites relating relative dielectric constant and soil conductivity.

$$\beta = 2\pi f\,(\varepsilon_r\,\mu_r/2)^{0.5}\left\{\left[1+(\sigma/2\pi f\varepsilon)^2\right]^{0.5}+1\right\}^{0.5} \quad \text{(B.5)}$$

where for both equations,

V_m = velocity in the material (soil), m/s;
β = attenuation coefficient, nepers/m;
c = velocity of light in vacuum, 3×10^8 m/s;
ε_r = relative dielectric constant, unitless;
$\varepsilon = \varepsilon_r\,\varepsilon_o$;
μ_r = relative magnetic permeability, unitless;
σ = soil conductivity; and
f = frequency of the wave, Hz.

In the case of vacuum, where $\sigma = 0$ and $\varepsilon_r = \mu_r = 1.0$, the velocity of the wave is given by $V_m = (\varepsilon\,\mu)^{-0.5} = 2.9979 \times 10^8$ m/s = ~300 mm/nanosecond. Because the relative magnetic permeability of most soils is 1.0, the velocity of the waves typically depends only on the dielectric permittivity. As shown in Table B.2, electromagnetic wave speed varies from 33 mm/ns in water to 300 mm/ns in vacuum. For most geological materials, the electromagnetic speeds range between 60 and 175 mm/ns.

The attenuation can be estimated by substituting Equation B.5 into Equation B.1 and expressing the results in dB. [Attenuations can be expressed in either dB or nepers, depending on whether 10^γ or e^γ is selected (base 10 or base e). They are related because $e = 10^{0.4343}$. $E/E_0 = e^\gamma = (10^{0.4343})^\gamma$, where γ is in nepers. Expressing the attenuation in dB, dB = $20 \log(10^{0.4343})^\gamma = 20 * 0.4343 * \gamma = 8.686\gamma$. Or 1 neper equals 8.686 dB.] The strong dependence of attenuation on soil type and moisture content limits the application of GPR to pipe location. In dry, sandy soils, GPR works for finding buried utilities such as gas pipe. However, for wet and clay soils, the waves attenuate rapidly, limiting depth of detection to less than 4 ft. A substantial amount of research effort in improved signal processing, arrays of single frequency antennas, and greater power extended the range a modest amount, but not nearly enough for deeply buried objects.

Reflection of EM Waves

In general, reflection of EM waves depends on differences in the wave velocity in soil and the pipe or the fluid in the pipe. For nonconducting natural-gas pipes, this means the amount of reflection depends on differences in the relative dielectric constants of the soil and natural gas. If the object is large compared to the wavelength, the fraction of reflection, *R,* can be calculated by Equation B.6:

$$R = (V_2 - V_1)/(V_2 + V_1) = \left[(\varepsilon_2\,\mu_2)^{0.5} - (\varepsilon_1\,\mu_1)^{0.5}\right]/\left[(\varepsilon_2\,\mu_2)^{0.5} + (\varepsilon_1\,\mu_1)^{0.5}\right] \quad \text{(B.6)}$$

Because $\mu_1 = \mu_2 = 1$ for most soils, the amount of reflection depends on the dielectric permittivities. Dry sand and dry clay can have relative permittivity of ~3, which is similar to plastic pipe's relative permittivity of 2.3. However, the relative permittivity of natural gas is effectively 1. Thus, even if the soil and pipe permittivities are equal, GPR will see the interior of the pipe as a hole in the ground. For $\mu_1 = \mu_2 = 1$ and $\varepsilon_2 = 1$ and $\varepsilon_1 = 3$, the reflection coefficient is 0.27, or 27%.

Acoustic Attenuation in Soil

Acoustic or vibration waves can propagate in soil and can be used to detect the presence of buried pipe. Detailed modeling of wave propagation in soil is a complex subject because of the large range of soil types and particle sizes and the presence or absence of water in the soil pores. As a result, many models attempting to describe acoustic vibration propagation have been developed. However, they are specific to the conditions being modeled. A more direct approach is to make measurements on the attenuation of sound waves as a function of frequency. The coefficient of attenuation of sound vibrations in soil can be obtained by fitting data with Equation B.7:

$$\alpha = \alpha_s\, x\, f^n \quad \text{(B.7)}$$

where

α_s = the attenuation coefficient describing the particular soil;
x = distance propagated in the soil;
f = the frequency of the wave; and
n = a number between 0.5 and 3.

Oelze et al. made a series of velocity of sound and attenuation measurements in six mixtures of soil (*8*). The clay content ranged from 2% to 38%, silt from 1% to 82%, sand from 2% to 97%, and organic material from 0.1% to 11.7%. They also used four levels of moisture content and two levels of compaction. Their soil samples were sieved to remove particles greater than 2 mm. A total of 231 evaluations were made to measure the soil properties. Their measured velocities ranged from 280 ft/s to 850 ft/s. Attenuation values ranged from 3.6 to 29.3 dB/ft/kHz. Their values for n were all equal to 1.0. GTI made measurements in a large bed of "pitcher's mound clay," a commercially available soil made from a mixture of clay and sand, often used for baseball diamonds (*9*). The results were velocity = 500 ft/s, α_s = 5.1 dB/ft/kHz, and n = 1. These values are in the same range as Oelze's work. Acoustic waves tend to be more suited for soils that are wet and clay rich, so they are a good compliment to GPR.

An illustration of the effect of frequency on attenuation can be obtained by considering a soil with α_s = 5.1 dB/ft/kHz and n = 1. For an acoustic wave of frequency 500 Hz that

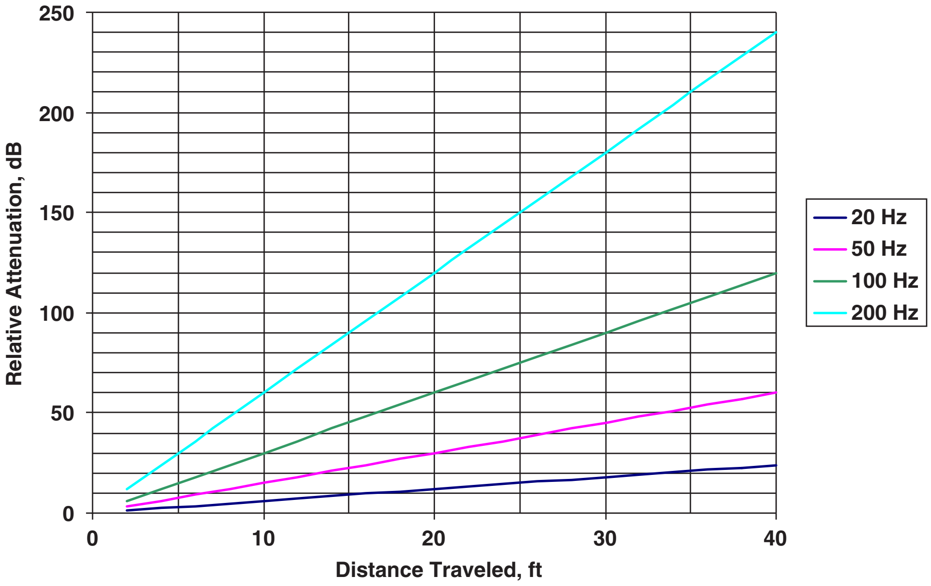


Figure B.3. Graph of the attenuation of acoustic waves as a function of distance traveled for four frequencies. In each case, the attenuation coefficient is 30 dB/ft/kHz.

travels 6 ft, the attenuation is 5.1 × 6 × 0.5 = 15.3 dB [dB = 20 log (A/A_o), and $A = A_o\ 10^{dB/20}$]. A 15.3-dB attenuation is a reduction in signal amplitude of a factor of 5.8. If a frequency of 5,000 Hz were used instead, the attenuation would be 153 dB, or a reduction in signal amplitude of $4.5 * 10^7$. A pipe buried 3 ft deep would be detectable at 500 Hz but not at 5,000 Hz. Figure B.3 plots attenuation as a function of distance for four frequencies for a soil with an attenuation coefficient of α_s = 30 dB/ft/kHz. As the graph illustrates, even in highly attenuating soil, a 20-Hz wave will be attenuated by only 25 dB after traveling 40 ft.

The same restrictions (see discussion in the next section) on maximum wavelength and the ability to detect a buried cylindrical object also hold true for acoustic waves. However, there is more than one velocity associated with sound waves because sound propagates in more than one mode. With longitudinal waves, the particle motion is back and forth along the direction of travel. S-waves have particle motions perpendicular to the path of the wave. S-waves travel at approximately one-half the velocity of longitudinal waves. Figure B.4 plots the wavelength versus frequency for four velocities of sound. Choosing to use S-waves rather than longitudinal

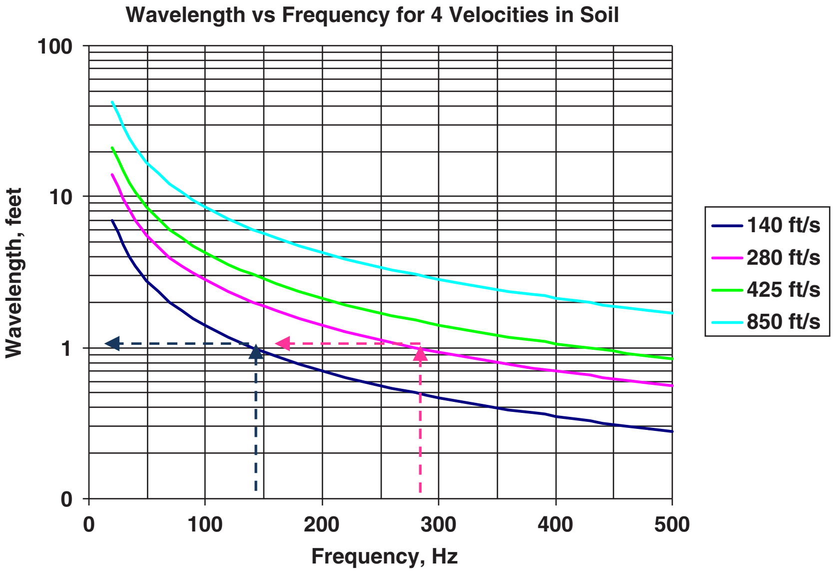


Figure B.4. Graph of the wavelength of acoustic waves as a function of frequency for four velocities.

waves can have advantages. For example, in a soil with a longitudinal velocity of 280 ft/s, a wave with a frequency of 280 Hz will have a 1.0-ft wavelength, as indicated by the pink arrows. Because S-waves travel at half the velocity of longitudinal waves, the soil would have 140 ft/s shear velocity. A 140-Hz S-wave will also have a 1.0-ft wavelength, as indicated by the blue arrows. The ability to see a 1-ft-diameter object is the same; however, the lower-frequency S-wave will suffer less attenuation and could detect the object at a deeper depth.

Limits on the Minimum Frequency to View Buried Pipes

The attenuation of both electromagnetic and acoustic waves decreases with decreasing frequency. This implies that low frequencies (i.e., long wavelengths) should be used to increase the depth at which pipes can be detected. However, the fundamental nature of waves places two limits on the wavelength used to see a cylindrical object with reflected radiation. First, the wavelength must be equal to or shorter than the circumference of the pipe. If the wavelength is an order of magnitude or more smaller, the object acts as a mirror. If the wavelength is too long, the wave passes by the cylinder with minimal reflection. The transition between the two occurs when the wavelength equals the circumference of the pipe. The second limit occurs when trying to differentiate two closely spaced objects, such as two parallel pipes. To detect that two closely spaced pipes are present, the wavelength must be shorter than four times the distance between the pipes. Thus, there is a limit on the maximum wavelength. Equation B.8 gives the relationship between minimum frequency, maximum wavelength, and wave velocity. Because attenuation depends on frequency, the restrictions on wavelength place a practical limit on the depth of detection.

$$f_{\min} = V_m / \lambda_{\max} \qquad \text{(B.8)}$$

where

$f_{\min}$ = minimum frequency, in Hz;
V_m = velocity of the wave, in m/s; and
$\lambda_{\max}$ = maximum wavelength, in meters.

Service pipe can be as small as 0.5 in. (0.0127 m), with a circumference of 1.57 in. (0.040 m). To detect that size pipe with GPR in a soil of velocity of 1.0×10^8 m/s (100 mm/ns), the frequency should be greater than 2.5 GHz. This suggests that GPR using 400- or 500-MHz antennas may have a hard time detecting 0.5-in. services. This is borne out by field experience.

These limitations on minimum frequency apply only to techniques that use a "beam" of waves to reflect from the pipe. They do not apply to techniques in which the signal is generated on or in the pipe. For example, electromagnetic pipe locators have been used successfully for decades at frequencies of 400 to 200,000 Hz. The wavelength at 200,000 Hz is approximately 1 mile, with the lower frequencies being longer. Similarly, acoustic techniques that inject an acoustic signal into the conduit can also use low frequencies/long wavelengths.

Nonplane Wave Aspects

So far the discussion has considered plane wave properties of acoustic and EM waves. A plane wave propagates with wave fronts as flat planes. This is a useful approximation that highlights critical properties and limitations of waves and yields an estimate of depth of penetration and resolution. However, in most cases, plane waves are an approximation. Most waves start propagating with cylindrical or spherical wave fronts. These wave fronts are distorted as the waves propagate through the soil and are reflected and diffracted from buried objects and soil layers. Substantial improvements in imaging have been made by understanding and using the nonplane wave aspects of acoustic and EM waves. These include geometric spreading, source directivity, inclined reflection, and scattering for the detection of point reflectors. For example, as waves travel in the ground, they are reflected and diffracted by the soil and objects in the soil. Reflection and diffraction are fundamentally different physical phenomena. Techniques are being developed to separate refracted and reflected waves, yielding additional information about buried features. Several references discussing these phenomena are given in the bibliography for this appendix. Nonplane wave aspects are important for detailed understanding, and the research team will include such effects in the technology developments. However, nonplane wave considerations do not change the basic conclusions about attenuation, the limits on depth penetration, and the minimum frequency to see an object.

Description of Specific Technologies

This section reviews several technologies for locating and tracing buried pipe.

Ground-Penetrating Radar

GPR works by launching pulses of electromagnetic energy into the ground. The resulting wave propagates through the ground and is reflected by subsurface targets or at interfaces between soils with different dielectric constants. The radar measures the time taken for a pulse to travel to and from the target, which indicates its depth and location. As discussed above, soil properties affect the velocity of the waves and the depth of penetration. The depth of the object is calculated by multiplying the travel time by the wave velocity. Thus, errors in the velocity affect the accuracy of depth determination. However, the lateral location of the pipe is not affected. The depth of detection depends on the soil conductivity, the power of the transmitter, and the sensitivity of the detector. As illustrated by Equation B.5, soil effects are exponential with round-trip travel distance. Because much infrastructure is buried in highly attenuating soil, additional locating technologies are needed to complement GPR. GPR works best in sand and has the most difficulty in highly conductive soils, such as wet clay.

Electromagnetic Pipe Locators

An electromagnetic pipe locator works by detecting the magnetic field generated by current flowing through a metal utility or a tracer wire. This current can be injected via direct connection or by induction into the pipe. An operator walks along the suspected path of the pipe carrying an instrument that can detect magnetic fields. Alternatively, the magnetic fields can be created in a sonde that is pushed through the utility. Sondes are used in nonmetallic conduits. The lateral range of the sonde is limited, so the operator must keep close to it as he follows its path. It is also possible to use a passive technique without coupling a tracer signal into the pipe. The passive technique relies on ambient electromagnetic signals created by radio and electric power lines and by other ground currents that follow the pipeline. However, if the ambient signal is not present, the pipe cannot be found.

In the active EM technique, it is necessary to create an electric current in the pipe. Thus, only metal pipes or copper wires placed near the pipe can be detected. The resulting alternating current creates a detectable electromagnetic field along the pipe. Ideally, the magnetic field is cylindrical, with the pipe at its center. However, the field is not always cylindrical, especially at pipe bends. Most EM pipe locators are two-piece systems: one to induce the field, and the other to detect it. The induction unit is placed at a known pipe location. The detector is moved over the suspected location of the pipe. In theory, direct currents could be used. In practice, they are not used because alternating currents are easier to detect. The magnetic field oscillates at the same frequency as the current. The frequencies used range from 50 Hz to 480,000 Hz.

The amount of current on the pipe, not the voltage, determines the magnitude of the magnetic field. In order to conduct current, there must be a complete loop or path. The metal pipe or tracer wire provides one path. The soil provides the return path. Both the dielectric constant of the soil and its conductivity affect the return path. The soil surrounding the pipe behaves as if there were a series of small capacitors attached to the pipe. The larger these "capacitors" are, the easier it is to couple current into the pipe. Capacitance increases with the surface area of the pipe. Thus, the pipe diameter affects the distance a signal will carry. A higher soil dielectric constant will also increase the capacitance. Higher soil conductivity improves the functioning of the soil as a return path. Although higher dielectric constant and conductivity increase the amount of current coupled into the pipe, they also make it easier for the current to drain away as the current flows along the pipe. The same signal strength will leak away over a much shorter distance from a large pipe than from a small one. For the same signal strength, a higher-frequency signal will decay away faster than a lower frequency. If the pipe is bare or has holidays in the coating, higher-conductivity soil will also drain away the current creating the signal. Many locators provide a choice of frequencies so that the operator can optimize the instrument for the conditions.

The locating instrument uses a coil of wire for each sensor. The magnetic fields generate a voltage in each coil. Two coil orientations can be used to detect either a peak in the signal or a null over the pipe. A peak is measured over the pipe when the axis of the coil is oriented parallel to the ground and perpendicular to the pipe. In ideal conditions, the magnetic field surrounding the pipe is cylindrical, with the strongest signal directly over the pipe, as illustrated on the left side of Figure B.5.

For deeply buried pipe, the variation in signal strength as a function of distance from the pipe on the surface of the ground is small, and precise pipe location is difficult. In such cases, the null method, with the axis of coil oriented perpendicular to the ground, can be used. In the null method, the signal drops to zero at three locations—far from the pipe on each side and directly over the pipe. The relationship of the measured null to the actual location of the pipe in the null

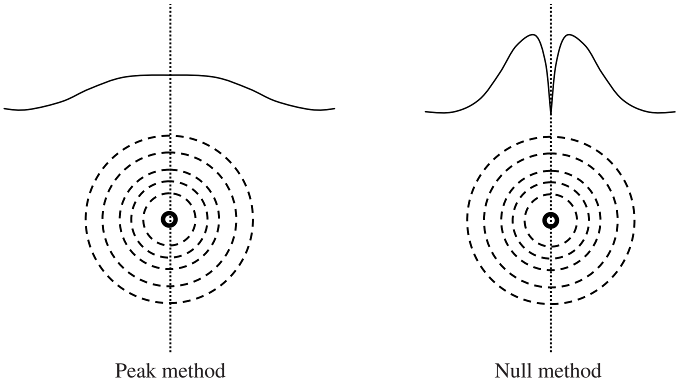


Figure B.5. Comparison of peak and null pipe location signals.

method can be skewed when interfering signals from adjacent pipe are present. In such cases, the peak and null signals do not occur in the same place.

The best locating results are obtained when the current lead is connected directly to the pipe. For cases where this is not possible, electromagnetic induction is used to couple current into the pipe. The higher the induction frequency, the more signal is coupled into the pipe. Another advantage of higher frequencies is that it is easier for them to jump across insulating joints. Higher frequencies have the disadvantages of jumping from the pipe being located to adjacent piping and attenuating faster.

As discussed above, many factors enter into the ability to locate pipe. Because of those factors, the depth to which EM locators work is a difficult question to answer. As part of a confidential survey of natural-gas utilities on issues related to EM location, GTI asked at what depth they begin experiencing problems with accuracy in locating facilities. The answers ranged from 6 to 14 ft, depending on the installation, type of pipe, and the soil conditions.

Magnetic Pipe Locators

Magnetic pipe locators detect the static magnetic field surrounding a ferromagnetic object. When these types of utilities are in the presence of the earth's magnetic field, a disturbance in the field is generated that can be detected by magnetometers. Such a field has north and south poles. The field is created by residual magnetism on the object, or it is induced by the earth's magnetic field. Magnetometers are passive devices that respond to ferrous materials only. However, magnetic detection of buried power cables is also possible because those cables emit magnetic fields. In practice, the magnetic field generated by buried power cables is often distorted to some degree because of the presence of magnetic minerals in the soil, surrounding metallic pipes, and other power cables in the vicinity, resulting in several superimposed fields.

Several types of magnetometers are available for use. Relative to other metal detection technology, magnetometers typically perform better for large, deep ferrous utilities. One type of magnetic locator has one sensor, and the operator must detect changes in the absolute magnetic field. Another version of the instrument has two sensors, called gradiometers, which are separated by a fixed distance. A signal is identified when the magnetic field strength at the two sensors is different. This configuration allows the gradiometer to perform with greater tolerance to cultural interference and improves the ability to detect smaller ferrous utilities. The range of detection for magnetometers is strongly dependent on the strength of the field.

Electromagnetic Induction Metal Detectors

Electromagnetic induction (EMI) metal detectors work either by rapidly turning the current on and off or by using a sinusoidally varying current within a coil on the instrument. This varying current generates a changing primary magnetic field into the ground and induces electrical eddy currents in any nearby metallic objects. This secondary magnetic field is then measured and used for the detection of buried metallic utilities. EMI metal detectors differ from magnetometers in that they are not limited to the detection of only ferrous metals but rather may detect any conductive metal. In addition, EMI detectors are usually less affected by ambient conditions than are magnetometers. The two main types of EMI metal detectors are time-domain electromagnetic induction (TDEMI) detectors and frequency-domain electromagnetic induction (FDEMI) detectors.

Time-Domain Electromagnetic Induction

TDEMI uses a coil of wire parallel to the surface of the ground to create an electromagnetic pulse. This pulse temporarily induces eddy currents in conductive objects. After the pulse is turned off, the electromagnetic fields created by the decaying eddy currents are detected. The magnitude and rate of decay of the fields depend on the electrical properties and geometry of the medium and any subsurface objects. The time of arrival may give information on the depth of subsurface metallic bodies. The currents in the earth decay or dissipate first, followed by the induced currents in metallic objects (see Figure B.6).

In Figure B.6, the top series shows square-wave pulses of the transmit signal, which decay at a rapid pace when no conductive object is present. The bottom trace shows the extended decay observed from a conductive object. Arrows indicate a single time-gate measurement. Multiple time-gate measurements may be made throughout the decay period.

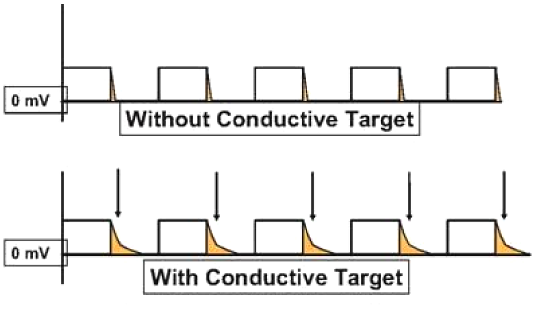


Figure B.6. Operation of a TDEMI.

One version of this technology is being developed by Underground Imaging Technologies (UIT) as part of their digital multisensor system. This system incorporates both TDEMI and GPR methodologies. EMI is complementary to GPR because it is more useful in soils with high clay/moisture content. The TDEMI component of the system consists of several transmit (Tx) and receive (Rx) coil pairs. It has fully programmable Tx and Rx parameters. As usually configured for characterizing buried objects, it measures the EMI decay from 0.04 ms to 25 ms. In detecting subsurface utilities, different-size pipes display different response characteristics. The wide range of response behaviors depends on the Tx/Rx configuration, which reflects the effects of different combinations of transverse and axial response components.

The basic mono-static EMI response for a metal pipe or conduit occurs in two stages. As the primary field shuts off, eddy currents are excited at the surface of the object and then decay rapidly as they diffuse into the object. During this phase the EMI response decays algebraically. As the eddy currents spread throughout the object, the response shifts over to an exponential decay whose rate is determined by the physical properties of the object (diameter, wall thickness, magnetic permeability, and electrical conductivity). Different pipes or conduits have different combinations of algebraic and exponential decay parameters, and these parameters vary depending on how the line is being excited. The complete set of the sensor array data can be processed using EMI inversion algorithms to determine the basic set of parameters that fully characterize a utility line's EMI response. The complete set of response parameters forms a unique feature vector that may be used for reliable identification and classification of underground utility lines.

Frequency-Domain Electromagnetic Induction

The basic operating principle of the FDEMI method involves a transmitter coil radiating an electromagnetic field at one or more selected frequencies to induce an electrical current (secondary EM field) in the earth and subsurface objects. Depending on the size of the instrument and the frequencies generated, the system can detect metallic objects at varying depths and sizes. Because the signals from the subsurface metallic objects are recorded during a time when the primary signal is still on, these instruments measure the induced currents of the conductive materials differently than the time-domain instruments. FDEMI instruments measure differences in the phase and amplitude between the received signal and the transmitted signal. The presence of subsurface metallic items results in changes in the measured parameters.

Acoustic Locators

Acoustic locators use sound waves to detect the location of the pipe. Several approaches are in various stages of development.

Active Acoustic Detection

In the active acoustic technique, a known signal is injected into the medium being carried by the pipe. The signal can be generated by several methods, including an acoustic driver connected to the service of a natural-gas line, a water hammer generated at a hydrant, or an acoustic driver hanging in a sewer manhole. The acoustic wave propagates through the medium in the pipe, not along the pipe wall. However, as the signal travels in the fluid, a portion of the signal couples into the pipe wall, causing it to vibrate. These vibrations propagate to the surface of the ground, where they are detected. Figure B.7 is a schematic of a two-sensor version of the active acoustic technique.

A similar approach performs passive detection of the acoustic signatures of various utilities. However, instead of injecting a signal into the medium inside the pipe, the passive technique uses preexisting sounds. Passive noises include flow noise generated by natural gas or water flowing through the pipe. Because the frequency ranges are similar, the passive and

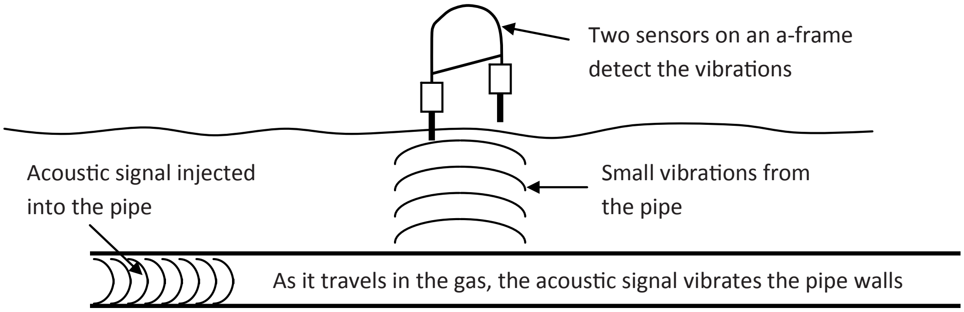


Figure B.7. Sound injected into the gas in the pipe causes the pipe to vibrate. The resulting waves radiate to the surface, where they are detected.

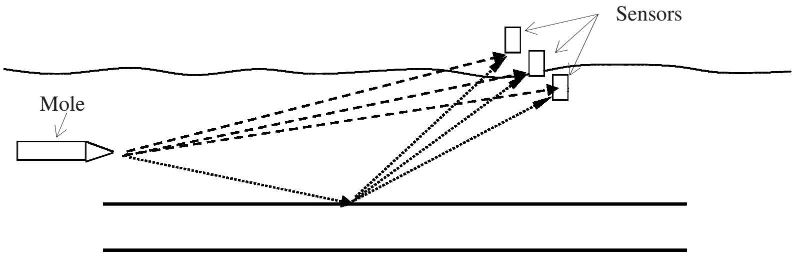


Figure B.8. The moling equipment creates acoustic waves that reflect from the pipe and also travel directly to the sensors.

active techniques can be implemented with the same sensors, signal-processing hardware, and readout display. The difference is that the active technique requires injection of a signal. The passive approach has the advantage of not needing access to the inside of the pipe. The disadvantage is that there is no guarantee a useful signal is present.

The commercial application of the active acoustic technique has been directed at locating plastic natural-gas mains. Radiodetection and Metrotech previously marketed acoustic pipe locators that were able to locate plastic pipe buried a few feet deep. A French company, MADE, is currently marketing a similar acoustic locator called the Gas Tracker. The Radiodetection unit used frequencies of 250 and 500 Hz. As the discussion on acoustic attenuation in soil illustrated, such frequencies limit the depth of penetration. The use of much lower frequencies should extend the depth of detection.

An approach in the development stage uses moling equipment to generate the acoustic signal. Figure B.8 is a schematic of this approach. An array of sensors is placed near the suspected location of the pipe. Impact vibrations from the mole are used as the signal source. Some of these vibrations propagate directly to the sensors. If a pipe is present, some of the vibrations also reflect from the pipe to the sensors. Cross-correlation is used to determine the presence and location of the pipe. This technique uses frequencies near 1,000 Hz with application to pipe a few feet deep.

Seismic Detection

Seismic detection of buried structures is a well-developed technique used to survey for water table, bedrock, oil-bearing structures, and geologic layers of interest. Seismic waves are generated at the surface of the ground. As illustrated in Figure B.9, these waves propagate to the geologic structure, where a portion of the waves reflects back to the surface of the ground. This approach operates in the far field, which means the distance to the structure is large compared to the wavelength. The equipment is expensive. The analysis techniques are not directly applicable to detection of "near-surface" structures—structures within tens of feet of the surface—for two reasons. First, the surface soil properties are different than deeper rock. Second, buried utility structures are in the "near field" where the wavelengths are similar to the distance to the objects. This complicates the signal analysis.

Sonar-type approaches for locating small-diameter pipe 3 or 4 ft deep have also been tried. An acoustic wave is generated directly over the pipe. It travels to the pipe, where some of the sound is reflected back to the surface. These approaches have been only partially successful because the 1,000-Hz frequencies needed to see the pipe are strongly attenuated and because the soil has not stopped vibrating from the initial generation of the sound wave before the highly attenuated wave returns.

Another approach is under development to detect and locate sewers and is part of the proposed development work of this project. Figure B.10 is an illustration of this approach.

Two sound generators are used. One large-amplitude source creates horizontal shear waves. The second creates both horizontal and vertical shear waves. The combination obtains information on the velocities of sound at different depths in the soil, which in turn is used to determine the location and depth of the pipe.

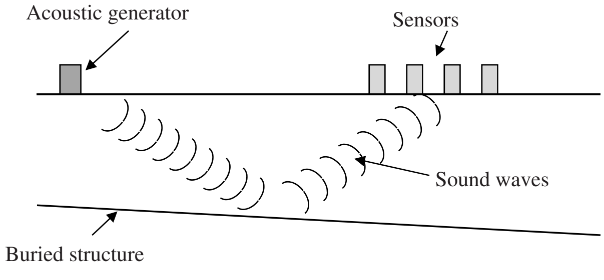


Figure B.9. Seismic waves can reflect from buried structures and be detected at the ground surface.

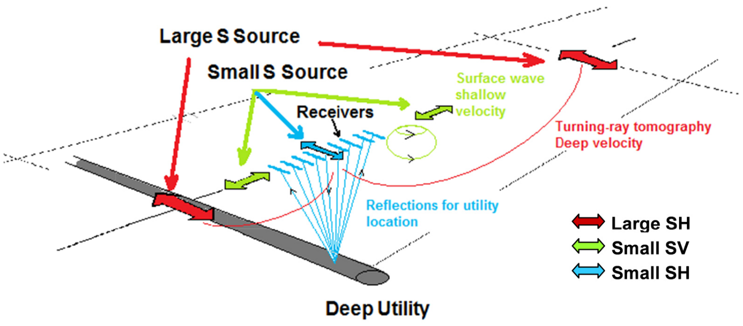


Figure B.10. Acoustic S-waves offer promise for locating deep utilities.

Inertial Navigation

Internal mapping starts at a known location of the buried utility, inserts an instrument into the pipe, and moves the instrument through the pipe. New and emerging inertial navigation system (INS) instruments use a combination of accelerometers, gyroscopes, and odometers to measure the distance the tool has moved and the changes in orientation of the tool. Accurate measurements of angles and distances are used to calculate the relative position of the tool to the entry point. These values are stored and downloaded to a laptop computer. A 3-D map of the pipe position is obtained. In principle, INS can be used from one entry point and travel for long distances through the pipe. However, the range of an inertial mapping tool is limited by cumulative error; the accuracy slowly degrades with distance from the insertion point. One of the more accurate INS tools quotes tolerances of +0.25% in the x and y (lateral position) and +0.1% in the z (depth). This results in a possible position offset of 12 in. in 400 ft, and 5 ft after a distance of 2,000 ft. The accuracy of INS location will improve as angle-measuring sensor technology becomes more accurate. Accuracy can also be improved if the locations of the pipe are known at one or more discrete positions.

Smart Tagging

Another approach to buried utility location is to bury indicators, or smart tags, that can be interrogated from the surface of the ground. Tags could be installed inside the pipe with robotics or attached to pipes before being directionally drilled into the ground. A reader would be used to determine the facility location. Systematically adding tags during other operations would make facility location easier in the future.

Smart tags contain information that can be interrogated from aboveground. One version of these, RuBee-enabled underground wireless pipe location and relocation systems (RuBee tags), is being developed and commercialized by Visible Assets, Inc. (VAI) for a broad range of applications. RuBee tags are based on the open IEEE 1902.1 standard. IEEE 1902.1 is a wireless, two-way, peer-to-peer transceiver protocol. They may be simple identity tags with only an IP address, or they can have a four-bit processor with 500 to 5,000 bytes of static memory, optional sensors, and signal-processing firmware. Previous attempts to use buried radio frequency identification (RFID) detection have not been successful, in part because the high frequencies used cannot penetrate deeply into the soil. RuBee is not like RFID, because it is a packet-based protocol and operates at a frequency (131 KHz) that can be detected even when deeply buried. The low operational frequency permits long battery life—up to 20 years on a coin-size CR2525 lithium battery. The range can be a few feet to more than 70 ft, depending on tag and antenna design. Read/write ranges can be 40 ft underground. With extra antennas, RuBee can provide 3-D localization. The tags are low-cost and can operate in harsh, underwater environments.

The project proposes to create two prototype tag products focused on location of deeply buried facilities. These tags will be waterproof, explosion proof, and designed for an average underground life of 15 years, with a range of 35 ft. Tags will be programmed with three-axis location data and, optionally, other relevant information about the buried assets, and will have 500 bytes of onboard read/write storage. One prototype version is aimed at new construction and retrofit burial. The second version of these tags would be attached directly onto a pipe, either inside or outside. The form factor will be conformal to the shape of the pipe itself, with the long-term goal of manufacturing the tags as part of the pipe.

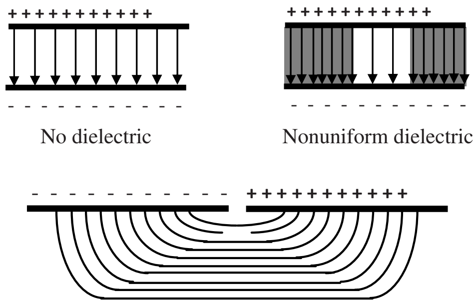
The project also proposes to create two handheld reader/locators. One RuBee reader and writer will be able to read data from the tag and also add useful information to the tag, such as GPS coordinates, pipe depth, date and time of installation, pipe type, size, content, and other field-critical data. The second reader/locator would have a longer range and only read data from the smart tag.

Infrared Thermography

Infrared thermography is a technique that detects temperature differences on surfaces. In concept, leaks and product flowing in the pipe create temperature differences between the pipe and ground. These in turn create a temperature field at the surface of the ground, with the highest or lowest temperature above the pipe. The technique has had limited success in locating water leaks, voids, and other similar anomalies. However, the temperature gradients at the ground surface are small for shallowly buried pipe. They became even smaller as the pipe depth increases. The technique has little potential for detecting deeply buried facilities.

Capacitive Tomography Imaging

Capacitive tomography is a technology in the early stages of development with potential for detecting buried facilities. One usually thinks of a capacitor as composed of two parallel, charged conducting plates separated by a small distance (see the top portion of Figure B.11). The space between the plates may be filled with a dielectric to increase the capacitance. Normally, the dielectric material is uniform. Any variations within the dielectric cause variations in the local electric field. The capacitive tomography sensor is composed of many plates, all in the same plane (see the bottom portion of Figure B.11). The technique applies an alternating current between each set of plates and measures the resulting steady-state electrical impedance under each plate. Variations among the impedances indicate the location of buried pipe. Capacitive tomography depends on differences between the relative dielectric constant and the electrical conductivity of the soil. Frequency range is much lower than GPR (100 kHz to 400 kHz); therefore, penetration depth is better. The image resolution is set by plate size and spacing, not frequency. Time of flight is not measured, so no high-speed signal processing is required. Experiments indicate that the capacitive tomography technique functions best in wet soil and has difficulty in dry soils—the opposite of GPR. The sensor sees deeper by decreasing the frequency. However, the lower frequencies also detect all the material between the surface down to the maximum depth. A method is needed to separate the near-surface features from the deeper features. Development issues include trade-offs between the size of each plate and the ability to detect changes in dielectric properties. The smaller plates required for higher resolution have very small capacitances, creating measurement problems.



In capacitive tomography, the plates are in the same plane.

Figure B.11. In a typical capacitor, the electric field between two parallel plates is perpendicular to the plates. In capacitive tomography, the plates are in the same plane.

Discussion of Advantages of Proposed Technologies

The wide range of pipe materials, diameters, and burial depths combined with the wide range of soil properties and their effects on pipe location technologies means that no single technique will work in all soil types. This is especially true for deeply buried facilities. A complementary set of tools is required. The goal of this project is to develop several prototype tools that can be used in proof-of-concept tests. This section summarizes how each proposed technology improves on the existing art.

Smart Tags

One approach to buried utility location is to bury indicators, or smart tags, that can be interrogated from the surface of the ground. Marker ball tags composed of a resonant coil/capacitor circuit have been used for shallow depths for many years. Previous attempts to use buried RFID detection with more information at deeper depths have not been successful, in part because the high frequencies used cannot penetrate deeply into the soil.

VAI proposes to create two prototype tag products that can be used at depths of 35 ft. These tags will be based on the open IEEE 1902.1 standard, referred to as RuBee tags. RuBee is not like RFID, because it is a packet-based protocol and operates at a frequency (131 KHz) that can be detected even when deeply buried. The tags for this project will contain 500 bytes of onboard read/write storage. The project also proposes to create two handheld reader/locators. One RuBee reader and writer would be able to read data from the tag and also add useful information to the tag, such as GPS coordinates, pipe depth, date and time of installation, pipe type, size, content, and other field-critical data. The other will work at greater depths but will only read data.

Inertial Navigation Systems

An inertial navigation system (INS) inserts a tool into the subject pipe. Sensors detect the orientation of the tool as a function of distance as it moves through the pipe. These data are used to calculate the position of the tool with respect to the entry point. For this tool, GTI will work with Geospatial and their commercially available Smart Probe to make operational improvements in three areas.

"Live" Insertions

Requiring the utility to be shut down and taken out of service before running inertial mapping tools is a significant limitation. Many pressurized lines cannot be shut down because of the critical nature of their services. Inserting the INS tool through a small hole in the pipe at operating pressure (called "hot tapping") will increase the practicality for locating deeply buried utility lines. GTI has developed hot-tap technologies for other applications. This experience will be leveraged to develop prototype fittings and techniques for live inertial mapping tool insertion.

Smart Tag Internal Benchmarking

The range of inertial mapping tools is limited by cumulative error. Because the angular measurements have error, the accuracy of the calculated position slowly degrades with distance from the insertion point. Corrections can be made if the true location of the pipe is known at discrete positions along the pipe. Smart tags can be installed at selected locations and used as a benchmark to enhance the accuracy of inertial mapping. There is another potential synergy between inertial mapping tools and smart tags. If the inertial mapping tools could also be used to install smart tags on the interior of a pipe wall, relocating these facilities in the future would be greatly simplified. One part of the smart tag project is the development of tags for deep-pipe applications. Another part is development of prototype tags that can be installed on the interior surface of the pipe during mapping.

Small-Hole Insertion

Excavation and restoration costs are a significant factor in determining the practicality of using inertial mapping tools. Developing installation techniques that reduce the size of the excavation, and therefore reduce the total cost of use, would also increase the feasibility of this technology. Keyhole technology is one of the largest research and development programs at GTI. It includes pavement cutting, vacuum excavation, and long-armed tool development, as well as protocol and standards development. The project team will create prototype long-armed tools and attachments to allow the inertial mapping tools to be installed in a keyhole.

Electromagnetic Noncontact Technology

EM pipe location using a sinusoidally time-varying current is the most widely used technique for locating buried metal pipe. A current is injected into the pipe, and an operator walks over the pipe carrying a detector. The depth of application is typically 10 ft or less. At some sites, metallic and nonmetallic facilities are buried too deeply for conventional EM pipe locators. However, where manholes provide access to nonmetallic facilities, INS can be used to map them. However, this will not detect adjacent metal pipe.

GTI proposes to develop a prototype tool that can be passed through a nonmetallic pipe and scan the surrounding soil volume for metal pipes. In this EM technique, a rotating EM field is projected into the soil. The projected field induces eddy currents in metallic objects, which in turn produce a detectable field. The rotating field is generated by a set of driven coils, so phased as to gradually rotate the driven field through 360° about a central axis. The primary frequency of the EM signal and the rate of the field rotation are independently adjustable. One or more sensing coils monitor the EM field as it rotates. Metallic materials within the range of the instrument disturb the EM field and are detected by the sensing coils. This will provide knowledge on piping within approximately a 10-ft radius of the sewer. Because the field is rotating, the tool will give the direction to the adjacent pipe, and more than one pipe can be detected. The prototype could also be lowered into a vertical borehole and used to scan the surrounding volume.

The GTI EM innovation prototype will be designed to be synergistic with technologies provided by other research partners, specifically smart tags and INSs. In addition to the EM frequencies required to locate buried metallic facilities, the prototype will scan frequencies used for several types of buried radio frequency (RF) location tags. The EM innovation prototype will be able to detect the presence of passive RF tags that have been used by utilities for several decades. Additionally, the prototype will be able to both detect and interact with the RuBee (IEEE 1902.1) smart tags being produced by VAI for this project. The EM innovation prototype will also be able to be used in conjunction with the INS and GPS technologies provided by Geospatial. The use of INS technology will greatly simplify the odometry portion of the work aboveground and when used in buried ducts.

Unlike traditional EM locators, the EM innovation prototype will detect metal piping without injecting a current into the pipe. The direction to the pipe is part of the information generated. Thus, the new tool will also be able to be used at the surface of the ground to detect piping. There would be advantages where parallel pipes exist. Conventional EM locators typically predict the existence of one pipe. With the new tool, signal returns from more than one direction will indicate the presence and location of two or more pipes.

Seismic Reflection Technology

The seismic reflection approach will be developed by UIT. The approach is to launch acoustic waves at the surface of the ground. These waves will propagate to the pipe and reflect to sensors on the surface of the ground. This development will be performed in collaboration with similar work proposed for the R01B project in which initial measurements of seismic properties of soils will be made to optimize receiver specifications. The R01B project is developing an S-wave seismic system for mapping dense, shallow networks of utilities. The R01C project will use similar techniques and will develop instrumentation and analysis techniques that could be complementary to detect and image deeper pipe.

The proposed technique improves on previous technology by using horizontal shear (SH) and vertical shear (SV) waves to detect the pipe. When compared with longitudinal acoustic waves of the same frequency, S-waves have a shorter wavelength. The shorter S-waves will yield improved pipe imaging.

With respect to the detection of small objects and utility targets, S-waves offer several distinct advantages over compressional waves:

- *Propagation velocity.* S-waves travel considerably slower than P-waves in unconsolidated soils. In many cases, the S-wave velocity is only about one-quarter that of the P-wave velocity. Given that the relationship between frequency, velocity, and wavelength is linear, the end result is that S-waves have much shorter wavelengths than P-waves in the same soil medium. This difference can yield up to 4 to 8 times better resolving power for S-wave detection of small targets, depending on soil properties, in comparison with P-waves when operating in the same frequency range.
- *Voids.* S-waves cannot propagate through fluids. A much higher percentage of energy is reflected from a void space for S-waves than for P-waves. Because very nearly all utilities are rigid pipes with an internal void space containing gas or liquid, S-waves are much more effective in detecting these types of objects.
- *Particle motion polarization.* Horizontally polarized SH-waves in particular exhibit higher reflections from elongated objects, such as pipes, when the polarization is parallel to the pipe-axis alignment than when transverse to the alignment. Therefore, SH-waves can provide more sensitive detection of small-diameter pipes when the general pipe alignment direction is known and used in the scanning process.
- *Wave-type conversion.* SH-waves do not undergo wave-type conversion and attendant energy partitioning between shear and compressional waves when transmitted through or reflected from horizontal contrasting interfaces. Therefore, with the polarization parallel to any intervening soil-layer interfaces, all the transmitted SH-wave energy remains available for detecting deeper objects.
- *Surface waves.* "Pure" SH-waves, not combined with contaminating P-waves or vertically polarized SV-waves generated at the surface, do not excite surface (Rayleigh) waves that can interfere with detecting and recognizing shallow SH-wave reflections.
- *Ambient noise.* Very nearly all the ambient noise generated by vehicular traffic and walking personnel, construction activities, and other sources of vibration is either P-wave or surface wave in nature. Therefore, SH-wave sensors have a much better ability to discriminate against most types of ambient noise than do their P-wave counterparts.

Changing from geophones to accelerometers will increase the frequency range available, which will help in the imaging. The increased frequency range combined with improvements in measurement system hardware and data processing methodologies should produce a system that is more field efficient for this project's purpose, less time consuming, less costly, and, most important, more effective at finding the deep targets. Electronically driven impact sources of two different sizes will be used for the signal source. The larger source will be used to collect lower-frequency data for large-scale velocity analysis, and the smaller source will be used to collect shallow velocity data, as well as reflection data, for imaging the target. Having a more complete knowledge of velocity over the depth range of interest allows accurate calculation of target location and depth.

Active Injection Acoustic Technology

GTI will develop a complementary acoustic technique for locating deeply buried pipe. A pulsed acoustic signal of known shape is generated in the interior of the subject pipe. This acoustic wave propagates through the medium in the pipe, not in the pipe wall. However, as the signal travels in the fluid, a portion of the signal couples into the pipe wall. Vibrations from the pipe wall propagate to the surface of the ground, where they are detected. This approach has two advantages. First, the sound waves travel only one way (from the pipe to the surface rather than from the surface to the pipe and back). Because attenuation is exponential with distance traveled, one-way propagation yields lower signal attenuation. Second, the sound waves are not imaging the pipe; therefore, lower frequencies can be used, again reducing attenuation and increasing the ability to detect pipe.

The prototype will measure the arrival times of the signals (time of flight). Because the signal is known, powerful signal-processing techniques can be used to discriminate the pipe location signal from background noise. The time-of-flight technique is relatively insensitive to variations in coupling between the sensor and ground.

In addition, GTI will use the same prototype tool to perform passive detection of the acoustic signatures of various utilities. Passive noises include flow noise generated by natural gas or water flowing through the pipe or acoustic hum generated in electrical cables.

Seismic and Acoustic Compared

One of the overall goals of the project is to develop a suite of complementary technologies. The seismic reflection method has the advantage at locations where the buried facility is inaccessible. The active method has some advantages over the seismic reflection method in those instances where there is access. Because the acoustic signal only travels from the piping to the ground surface, it suffers less attenuation. The active signal is injected into a particular pipe; therefore, the pipe is positively identified. The signal originates in the pipe instead of reflecting from its surface, relaxing the requirement that the wavelength must be scaled to the pipe diameter. The active method could use lower frequencies, which suffer less attenuation to achieve extra depth. The passive acoustic technique is expected to be effective on live electrical cables.

GPR and Seismic Compared

GPR has been the dominant utility location method used to date. It has quite effective resolution, it is fast to deploy, its raw data displays are reasonably straightforward to interpret, and it is reliable when ground penetration to the desired depths is practical. The problem is that GPR impulses, typically in the 80- to 500-MHz spectral range, do not penetrate to useful depths in a variety of soils common to utility burial environments:

- Clay;
- Caliche; or
- Wet or saline soils.

In short, the method does not work well when the soil is electrically conductive.

Seismic methods have been successfully used in the past to locate large utilities. In particular, those methods that used SH-waves have enjoyed the most success. The principal subsurface applications using SH-waves have employed the seismic reflection technique in locating caves, sinkhole voids, tunnels, and large underground sewer pipes. This is directly relevant to the detection of other types of utilities because most utility lines are in fact long, cylindrical targets containing either wires or fluids. In particular, the following results have been achieved using SH-wave seismic reflection methods:

- Location of a 2-ft-diameter tubular cavity in limestone at a depth of 70 ft.
- Location of underground coal and iron mines in New Mexico, Minnesota, Ohio, Indiana, Illinois, Iowa, Michigan, and New York at depths ranging from 100 ft to 1,000 ft.
- Location of voids along the top of jointed concrete storm sewers in Texas, New Jersey, and Louisiana.
- Location of large concrete pipes (>1-ft diameter) in California, Texas, and Louisiana at depths ranging from 10 to 50 ft.

Horizontally polarized shear waves generated by a vibrator source excited by a long–time-duration, linear-sine-wave sweep signal, and later processed by correlation analysis to produce reflection pulse wavelets, have been demonstrated to be effective in extremely noisy environments, including the following:

- SFO Airport, San Francisco;
- Downtown cities of Los Angeles, Minneapolis, and Des Moines;
- Operating oil refineries in Texas, Louisiana, and Minnesota; and
- Along the paved shoulders of interstate highways in California and Ohio.

Figure B.12 shows a chart of estimated quarter wavelengths for GPR signals at various MHz frequencies and seismic signals for various frequencies in the Hz to KHz range.

Since target detection is a function of wavelength, and since the detection capability in good soils of GPR, at say 400 MHz, is quite adequate, it seems appropriate to attempt to attain the same wavelengths for seismic impulses as are produced by GPR systems.

Figure B.12 uses an average value of dielectric permittivity for GPR in favorable soil and reasonable values for P-wave and S-wave velocities in near-surface soils. It is clear that if generating and propagating seismic waves of sufficiently high frequency is the problem, then using S-waves may provide an advantage. A quarter wavelength similar to that of a 400-MHz GPR signal in average soils for GPR can be produced with S-waves in the range of 700 to 1,000 Hz in soils good for seismic. However, it would be necessary to use P-waves of about 3,000 Hz to produce the same quarter wavelength in those same soils. UIT, Owen, and Psi-G have experience that suggests generating and propagating 3,000 Hz seismic waves is very difficult.

Work has been done with S-waves in depth ranges only a little deeper than is sought for normal utility mapping. Figure B.13 is an S-wave reflection cross section that shows a hyperbolic signature at the location of a sewer pipe at a depth of 11.6 m (38 ft). The maximum frequency detectable for this survey was about 700 Hz using an S-wave vibrator and a geophone streamer. This work is at least partial proof of the concept of using S-waves for detection of utilities. However, the survey in the example was expensive and difficult to process and would not be acceptable for use in normal utility mapping work as a result. On the basis of ideas under consideration for this project, which include appropriate modifications

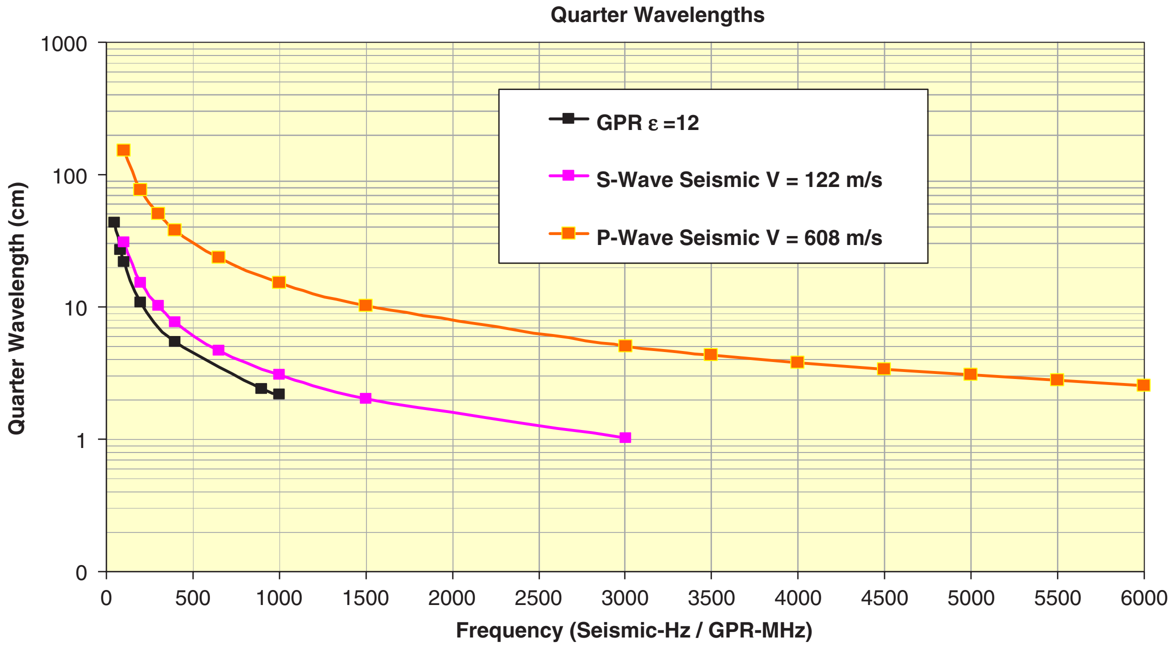


Figure B.12. Quarter wavelengths for GPR and seismic.

to field methodology and data processing, it may be possible to improve the time efficiency and cost of S-wave seismic surveys to make them both functionally and economically useful for utility mapping.

The use of multiple sensor, multiple antenna/transducer geophysical systems for improved mapping of buried utilities has been demonstrated and is used in the commercial market today. The integration of GPR, EMI, good positioning, and a 3-D workspace for first-order data fusion provide a big step forward in geophysical capabilities for mapping shallow utilities. Initial ideas and testing on the addition of a seismic component to the sensor package have validated the potential use of S-waves for mapping the types of targets sought for normal utility mapping in soils not compatible with GPR.

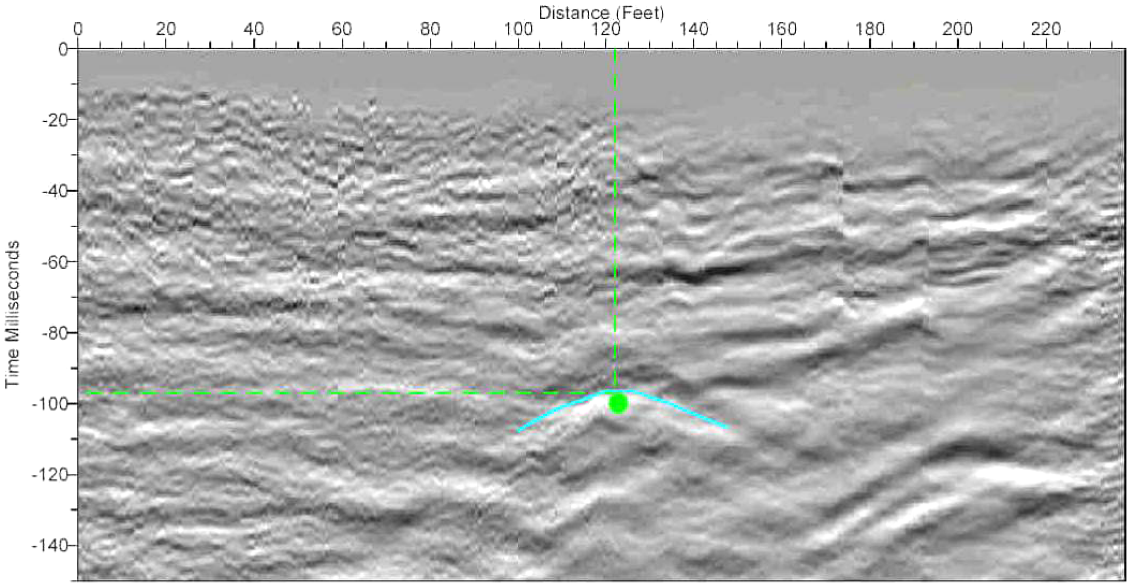


Figure B.13. S-wave reflection cross section with highlighted location of sewer pipe at 11.6 m (38 ft).

Table B.4. Locating Technologies Matrix

Technology	Horizontal Accuracy	Vertical Accuracy	Factors Effecting Accuracy	Ease of Use	Features	Examples	Comments
Electromagnetic pipe and cable locators	2–12 in.	5–20% of depth	Soil conditions, utility material and size, proximity of metallic structures, ability to directly connect to the utility	Moderate—audio and visual indicators require interpretation	GPS integration, 2-D signals, signal quality indicators, limited data output options	Metrotech, 3M Dynatel, and Heath Surelock	EM locators are the industry standard for routine utility locate and mark-out operations. While the devices are relatively simple to use, a fair amount of interpretation is required to pinpoint the location of the underground facility. EM locators cannot locate nonmetallic utilities and are dependent on the presence and condition of tracing wires.
Sondes	2–12 in.	5–20% of depth	Soil conditions, utility material and size, proximity of metallic structures, ability to directly connect to the utility	Moderate—audio and visual indicators require interpretation	GPS integration, 2-D signals, signal quality indicators, limited data output options	RD, Rycom, Ridgid	Sondes are an effective tool for locating plastic utility lines but require access to the internal pipe and are limited in the distances that can be located.
Ground-penetrating radar	2–24 in.	The vertical accuracy of GPR is high if the utility can be detected. Signal attenuation can result in depth penetrations ranging from 12 in. to 10 ft.	Soil moisture and conductivity, utility material and size, user experience and interpretation	Low—significant training and signal interpretation required	GPS integration, 3-D mapping output	Noggin SmartCart, Pipehawk, and US Radar	GPR used primarily by specialized service providers and SUE firms. Direct use by utility companies has been limited because of the high cost, training requirements, and variable performance in different soil conditions.
Acoustic and seismic locators	6–12 in. based on limited testing	Limited information available	Soil moisture and ground cover	Moderate	Limited data output options	MADE Gas Tracker, R01B and R01C	Commercially available acoustic locators require access to either the content of the pipe (gas) or the pipe (water). The primary advantage of acoustic locators is the ability to locate nonmetallic lines. GTI is developing an acoustic locator that does not require access to the pipe or the pipe contents.
Magnetic locators	Limited information available, but the technology is sensitive to interference.		Utility size and material	Moderate	Limited data output options	Geometrics, GEM Systems	The primary application for magnetic locating tools is large, deeply buried ferrous materials.
Electromagnetic induction	Limited information available for utility applications.					R01B	Similar to magnetometers, but can locate other nonferrous materials and is less sensitive to nearby metallic structures and conductive soil conditions.
Inertial navigation	Very precise but drifts with increasing distances without calibration. Tolerances are 0.25% of the distance in the horizontal direction and 0.10% in the vertical direction.		Distance traveled	High—minimal interpretation required	Output can be formatted in CAD or GIS.	Geospatial Smart Probe	Inertial navigation is not technically a locating device, but it can be used to map out the location of a pipe. This technology is particularly useful for deep or directionally drilled utilities. Use of the Smart Probe requires the line to be taken out of service, although developments for live applications are feasible.

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APPENDIX C

User Panel

The following solicitation was e-mailed to a group of candidates who had been identified by the R01B and R01C project teams as being end users of the technologies that were being developed by these projects.

Solicitation for R01B and R01C User Panel Members

"We are putting together a Users Panel for several ongoing projects within the Strategic Highways Research Program (SHRP) [sic]. The original SHRP program, administered by the Transportation Research Board (TRB), identified multiple projects in the area of highway infrastructure renewal. The SHRP2 program is executing many of these projects. The attached presentation describes several projects in the area of infrastructure renewal.

"There are two particular projects which this User Panel would provide input on. The commonality of these projects is that they both address the interaction between road renewal and buried utility infrastructure.

"R01-B is research into developing a multi-sensor geophysical platform (e.g. combining GPR, EM, and seismic). This platform is intended to locate all utilities down to about 5 feet in a single pass.

"R01-C is developing geophysical methods for the specific case of deep or stacked utilities. There will also be smart tagging of utilities for finding them later with a reader at the surface.

"The overall goal here is to develop better systems for mapping buried utilities ahead of highway renewal projects, and other types of construction.

"The User Panel will have about 10 members consisting of persons likely be in a position to actually use the technology in the future. The R01-B and R01-C project teams would engage the User Panel in a dialogue and seek feedback on the performance goals of the projects. We anticipate several web meetings per year, and maybe one in-face meeting if desired. This position is not compensated, but time will be minimal, and the in-face meeting if held will also be able to be attended remotely if expenses are an issue. The projects are slated to run 30 months, and we are about 6 months into them already.

"I suggested to the teams that you would be a good person to be on the User Group, as any technology coming out of this research would only be successful if persons such as yourself:

a) believed it had sufficient value to meet your and/or your clients' needs,
b) understood the market and existing technology well enough to recognize incremental advances,
c) And are held in sufficient esteem by your peers to influence the adoption of successful research.

"The SHRP2 project information can be found on this webpage, the specific projects for which we are soliciting a User Panel are under 'renewal': http://www.trb.org/StrategicHighwayResearchProgram2SHRP2/Public/Pages/Renewal_Projects_303.aspx"

This solicitation resulted in the following members joining the User Panel:

Bobby Nagel
Cobb Fendley
Houston, Texas

Rick Conte
Design Manager
Parsons Brinckerhoff

John L. Krause, Jr.
State Surveyor
Florida Department of Transportation
Tallahassee, Florida

James Mooney
Project Engineer
Consolidated Edison Company
New York, New York

Philip J. Meis
Principal Engineer/Vice President
Utility Mapping Services, Inc.

David B. Hale
Technology Assessment/Corporate Safety Officer
So-Deep
Philadelphia, Pennsylvania

Wayne Wilson
Kiewit & Sons
Southern California Office

Mike Parilac
Planet Underground
Manteno, Illinois

James E. Hodges
Vice-President, Engineering
Middle Tennessee Natural Gas
Smithville, Tennessee

APPENDIX D

Technical Support Information for Seismic Reflection Technology

Abstract

Underground Imaging Technologies (UIT) is developing a technology that makes use of seismic shear waves (S-waves) to image buried utilities. UIT is assisted in this work by their subcontractor, Geomedia Research and Development (GRD).

The proposed technique improves on previous technology by using horizontal shear and vertical shear waves to detect the pipe. When compared to longitudinal compressional waves (P-waves) of the same frequency, shear waves have a shorter wavelength. Given that the image resolution is determined by the wavelength, the shorter shear waves will yield improved pipe imaging. With respect to the detection of small objects and utility targets, shear waves offer several distinct advantages over P-waves.

S-waves also exhibit a polarization property that is useful. If the S-wave is horizontally polarized, with its primary direction of oscillation parallel to the pipe, then a strong reflection will be returned. This property of S-waves to interact strongly with elongated targets will improve the ability to distinguish buried pipes from background clutter, such as stones or other inclusions.

Technology Synopsis and Key Performance Indicators

Title: Shear Wave Seismic Reflection Location

Provider: Underground Imaging Technology

Targets: The gas or fluid in a pipe of any material.

Depth range: Up to a maximum of 20 times the pipe diameter in homogeneous clay soils.

Depth accuracy: At best, 10% of pipe depth in homogeneous clay soils.

Location accuracy: At best, 5% of pipe depth in homogeneous clay soils.

Application: At least five S-wave impact sources are recorded into a mobile array of oriented vibration sensors. Two of the five sources are positioned and analyzed with a view toward estimating the large-scale soil shear velocity variations in the survey area. Two shear sources are recorded to use surface waves to image near-surface velocity variations. The fifth source is positioned and analyzed to highlight the horizontal shear energy reflected from the gas or fluid in the pipe.

Basic principle: The target pipe is viewed as a large coherent scatterer sitting in a sea of small/strong or large/weaker scattering objects, such as tree roots, rocks, gopher holes, or filled excavations. The gas or fluid in a pipe will reflect shear-oriented energy when the pipe size is a significant fraction of the shear-energy wavelength. The pipe material will contribute a significant reflection of opposite polarity only if it is extremely strong or thick compared to the wavelength. An S-wave oriented parallel to an empty pipe will give a maximum in reflected energy. Once the reflected energy is identified, the background soil velocity is used to compute a location for the pipe.

Limitations: Soils can have highly variable velocities arising from original depositional features, anisotropic minerals and textures, or later excavations and modifications, which can severely limit location accuracies even for strong reflectors. The worst case is that some soil structures may have shadow zones where nothing can be imaged. Depth is expected to be more difficult to resolve than horizontal position because surface measurements resolve only horizontal, not vertical, velocities. Higher frequencies capable of imaging smaller pipe attenuate over shorter distances and scatter more strongly before the coherent reflecting pipe can be reached, giving a poor signal-to-noise and image resolution. It is also generally more difficult to both generate and record high frequencies as soils become weaker and more nonlinear.

Additional notes: Previous attempts at locating pipes and tunnels with reflection seismology have identified trade-offs between only a limited set of survey characteristics that influence imaging success. Technically successful surveys use large numbers of sources and receivers with extensive processing, resulting in a prohibitive time and cost for utility location. Most of these surveys resolve only larger targets by using source-receiver redundancy to compensate for the poor high-frequency response of sources and receivers. The first phase of this study is to develop and test sources and receivers in the appropriate frequency/wavelength ranges that will be used to characterize soil properties and target reflectance under field conditions. The results of this phase can then be applied to determine the cost–benefit trade-offs between source-receiver redundancy and survey cost to resolve a given target.

APPENDIX E

Technical Support Information for Active and Passive Acoustic Locating Technology

Abstract

Injection of an acoustic signal into the fluid medium within a pipe has long been pursued as a means of locating buried pipes. The technique was first applied to cast iron mains and later to plastic piping. Both of these materials have the attribute that there may be little or no electrical continuity along the main. Even in cases where a tracer wire is installed alongside a plastic main, the wire can become compromised by corrosion or other issues. In these instances, standard electromagnetic tracing methods cannot be used, because the main cannot support the tracer signal current.

Another technology that is used to locate poorly conductive or nonconductive piping is ground-penetrating radar (GPR). GPR technology works well under some circumstances but not all. Soils that are wet or mineral laden attenuate the radar signal in both directions—after launch from the antenna and again on the return trip after reflecting from a target. The other issue is the detectable target size: the target must be large enough to reflect detectable signal energy, and the wavelength of the radar signal must be comparable with the size of the target. Even in benign soils, small targets may produce little or no GPR signal.

Active acoustic technologies address some of the limitations of GPR and other reflecting technologies. Having the pipe radiate a detectable signal, acoustic or electrical, decreases the signal attenuation in that there is no longer the "round-trip loss" inherent in reflected signal techniques. The radiated signal can be introduced intentionally to the utility, or it may be intrinsic, as in the case of AC power conduits. A pipe-radiated signal also removes the restriction applicable to reflective systems that the pipe diameter be comparable to at least one wavelength of the signal.

The concept of locating plastic pipe using an injected sound signal and an array of surface sensors has been proved to work. Reducing the equipment required to something field-ready has been more problematic. In the 1990s, the data acquisition and processing equipment was bulky and expensive. Current technologies are being applied to drastically reduce the equipment size and cost.

The same acoustic technology can be used to passively detect buried facilities that radiate an acoustic signature. Examples of this are the 60-Hz vibrations emitted by buried electric power lines and the flow noise emitted by water or steam lines. GTI has extensive experience in the acoustics of utility systems as a result of developing several generations of equipment for acoustic pinpointing of gas leaks. Much of the signal processing technique being applied to the SHRP 2 R01C project was developed to differentiate a gas leak signal from the background.

Technology Synopsis and Key Performance Indicators

Title: Acoustic Location Using an Active Signal
Targets: All pipe materials.
Depth range: At least 20 ft; greater in some soil types.
Depth accuracy: The expected accuracy for pipe parallel to the surface of the ground is ±10% of the pipe depth. For example: 20 ± 2 ft.
Location accuracy: The expected accuracy is ±1 ft or ±10% of the pipe depth, whichever is greater.
Application: An acoustic driver or speaker is placed in contact with the fluid within the pipe to introduce the signal. In the case of potable water, a water hammer can be used to generate the signal. An array of acoustic sensors is placed on the surface of the ground to take readings.
Basic principle: The active acoustic pipe locator injects a known acoustic signal into the fluid (gas or liquid) inside a pipe using an acoustic driver or loudspeaker for air or natural gas or a water hammer generated at a hydrant. The acoustic wave propagates through the medium in the pipe, not in the pipe wall. As the signal travels in the fluid, a portion of the signal couples into the pipe wall. Vibrations from the pipe

wall propagate to the surface of the ground, where they are detected. Those signals are used to detect the position of the pipe and to estimate its depth.

Limitations: The overall depth range is limited by the power of the acoustic signal introduced into the fluid. The sound source must be in direct contact with the gas or liquid in the pipe. For a gas main, a service can be removed and the sound injected there.

Additional notes: Because the acoustic signal only travels from the pipe to the ground surface, it suffers less attenuation than reflection-based techniques. The active signal is injected into a specific pipe, positively identifying it. The signal originates in the pipe instead of reflecting from its surface, relaxing the requirement that the wavelength be scaled to the pipe diameter. Therefore, the active method can achieve extra depth by using lower frequencies, which suffer less attenuation. The technique lends itself to locating sewers and other unpressurized facilities because the acoustic driver can be placed or hung in a manhole.

Technology Synopsis and Key Performance Indicators

Title: Acoustic Location Using a Passive Signal

Targets: All pipe materials.

Depth range: The depth range depends on the strength of the passive signal.

Depth accuracy: To be determined.

Location accuracy: The expected location accuracy is ±1 ft or ±10% of the pipe depth, whichever is greater. This assumes that a reasonable passive signal is present.

Application: An array of acoustic sensors is placed on the surface of the ground to take readings. The facility being located radiates a characteristic sound signature in normal operation, such as flow noise or 60-cycle hum.

Basic principle: The active acoustic equipment can also be used in a passive mode for situations where a passive signal is generated by the normal operation of the pipe. Examples of passive noises include flow noise generated by natural gas or water flowing through the pipe and acoustic hum generated in three-phase electrical cables. In passive mode the active signal generator is not used.

Limitations: The overall depth range is limited by the power of the acoustic signal generated by the facility as a by-product of its normal operation.

Additional notes: Because the acoustic signal only travels from the pipe to the ground surface, it suffers less attenuation than reflection-based techniques. The signal originates in the pipe instead of reflecting from its surface, relaxing the requirement that the wavelength be scaled to the pipe diameter.

APPENDIX F

Technical Support Information for Scanning Electromagnetic Locator

Abstract

The Gas Technology Institute (GTI) is developing a scanning electromagnetic (EM) locator for metallic pipe. The scanning EM locator is based on an earlier GTI project that developed a metallic joint locator (MJL). The MJL technology was successfully demonstrated at several utilities and licensed by Sensit Technologies for commercialization.

The EM locators currently in the marketplace require that the locator be moved with respect to the pipe in order to find the pipe's location. The signal is presumably strongest when the locator is immediately above the pipe. The locating signal is injected into the pipe either by direct metallic connection or by induction.

The MJL was originally developed to find bell and spigot joints on cast iron piping. These joints can represent a 30% change in the cross section of the pipe in localized areas. It was also discovered during testing that it detects much smaller features, such as service tees and repair clamps. The MJL places a signal on the target pipe by induction and reads the induced eddy currents with a pair of coils in a differential configuration. If the MJL is moved along a featureless pipe there is a null signal. The presence of any metallic appurtenances on the pipe unbalances the differential coils and produces a signal.

From the discussion above, it can be seen that the MJL must be moved along the (assumed) centerline of the pipe to detect features. The addition of the rotating induction field for the scanning EM locator removes the necessity to have a priori knowledge of the pipe centerline. Not only the signal magnitude but also the angle from the cart centerline to the target can be captured. This also means that a featureless metal pipe will produce a signal as the induction field scans it once per rotation. This technique should also be able to resolve stacked metallic utilities by rolling the cart to one side of the stack to produce a view in which there is angular separation between the targets.

Technology Synopsis and Key Performance Indicators

Title: Scanning Electromagnetic Locator Using a Rotating Field

Provider: Gas Technology Institute

Targets: Metal, with greater sensitivity to ferrous metals.

Depth range: Approximately 20 ft.

Depth accuracy: Depth is inferred from multiple passes instead of being directly measured.

Location accuracy: Location is centered by moving the locator until a null is achieved.

Application: The technology is cart mounted and provides a signal indicating the location of buried metallic objects relative to the cart. The cart is moved about the target area to trace the buried facility.

Basic principle: The instrument consists of three sets of coils mounted on a narrow, wheeled cart. A central coil generates an EM signal that passes through the soil. The signal couples into buried metallic objects and is then picked up by two coils mounted at the extreme ends of the cart. The metallic object distorts the field, allowing it to be located between the two pickup coils by the null method. Additionally, the EM field is rotated perpendicular to the long axis of the cart to provide the angular direction of the metallic object with respect to the cart. This angular direction can be used to infer depth by making two parallel passes at the buried object.

Limitations: The overall depth range is limited by the power of the EM signal radiated by the driven coil. The indication returned by the target is directly proportional to the size of the target; large diameter pipes give a greater indication. The accuracy of the null location is affected by the baseline of the instrument versus the depth of the target. Using the angular bearing can "synthesize" a longer baseline by taking multiple, parallel passes at the same target.

Additional notes: It will be possible to run the device within a buried, nonmetallic facility such as a storm drain. Given that the rotating field sweeps out 360°, it is possible to locate metallic facilities below, alongside, or above the one in which the device is run. The same is true of lowering the device into a vertical borehole. With some modification, the device could also detect the presence of radio frequency (RF) tags buried in the vicinity.

APPENDIX G

Technical Support Information for Long-Range Smart Tags

Abstract

Visible Assets Incorporated (VAI) is developing long-range radio frequency identification (RFID) devices suitable for direct burial use. These devices conform to the IEEE 1902.1, or RuBee, communication protocol. These smart tags can be located from a distance and queried for a unique serial number and other user data. The tags developed by VAI incorporate low-power microprocessors and batteries with 20-year life expectancies. Future versions of these tags could incorporate sensors.

Smart tags have the potential to solve a number of issues with the locating of underground utilities. Once installed, smart tags greatly ease the problems associated with back-navigating to a particular feature and positively identifying it. Smart tag technology is complementary to that of GPS. The accuracy of GPS can be degraded by interference from buildings, weather, and other issues. Even under the best conditions, the *z*-axis accuracy of GPS is lower than the *x*-*y* accuracy.

A smart tag can be located to a relatively high degree of *x*, *y*, and *z* precision once the tag and its associated reader are within range of one another. One scenario might be to use an inexpensive GPS or physical landmarks to get within read range of a smart tag and then use the tag reader to get a precise location.

The expected range of the RuBee tags from VAI is on the order of 30 ft. This is in contrast to a range of 5–10 ft from other direct burial tags. The extended range opens up underground applications not previously possible. Smart tags can be attached to the exterior of deep utilities and so provide fixed reference points that are not disturbed by most excavation. The current practice is to locate short-range tags above deep utilities rather than at true depth. Over time, these tags may become dissociated from the features they were intended to identify.

Conformance with an IEEE standard allows tags to interact with readers from various manufacturers. This is in contrast to the proprietary data formats that are currently used for buried smart tags. In such cases, the end user is locked into tags and readers from a single manufacturer.

Technology Synopsis and Key Performance Indicators

Title: Smart Tags and Sensors for Deep Facilities
Provider: Visible Assets Incorporated
Targets: All pipe materials, as well as valves and mission critical assets.
Depth range: At least 20–50 ft.
Depth accuracy: The expected accuracy is ±10% of the pipe depth (to be determined).
Location accuracy: The expected accuracy is ±12 in. or ±5% of the pipe depth.
Application: Smart tags are placed internally or externally on buried facilities. Once in place, the active tags can be used to identify and locate these facilities. Specialized tags can also return sensor data about the facility. Some tags may be used on valves and other mission-critical aboveground assets.
Basic principle: RuBee IEEE 1902.1 is a peer-to-peer low-frequency standard that has been optimized for harsh environments. The tags can have a CPU, and memory, as well as sensors. Tags with a lithium coin-size battery (CR2525) have a proven life of up to 25 years. Projected life is 15 years of normal use.
Limitations: Data rates are about six to eight reads per second. Detection range may be enhanced, but this will reduce battery life.
Additional notes: RuBee is not blocked by water, and steel can actually enhance range.

APPENDIX H

Technical Support Information for Inertial Mapping Systems

Abstract

GeoDZ Inc. will demonstrate a commercially available inertial mapping system (IMS) that can be deployed inside a duct or pipe. The IMS can produce an accurate mapping of the path that it has traveled relative to its starting and end points. If the entry and exit points are located using a high-accuracy GPS, then the *x, y,* and *z* coordinates of the intermediate piping can be captured regardless of pipe material, soil type, or depth. The current IMS product cannot be used in live or pressurized pipe. The demonstrations under SHRP 2 Project R01C will be limited to storm drains or piping that is out of service.

Technology Synopsis and Key Performance Indicators

Title: Inertial Mapping for Utility Lines
Targets: All pipe materials.
Depth range: Unlimited, not dependent on soil types.
Depth and position accuracy: The expected position (or location) accuracy for pipe is ±0.03% from the closest known (GPS-surveyed) point. The term "position" is used because this is a mapping tool, producing *x, y, z* (3-D) coordinates in the state plane coordinate system (SPCS). The calibrated accuracy is computed by the following: $\text{Accuracy}_{3D} = d/500 * 0.15$, where d is the distance in meters from the closest GPS marker location. This could be the entry or exit point of the pipeline, or intermediate markers along the pipeline trajectory.
Application: The inertial mapping system (PROBE) is used in any open-ended or launch/trap-configured pipeline or conduit that is either empty or contains liquids, has minimal diameter restrictions or obstructions, and requires accurate 3-D mapping of the centerline and/or the precise trajectory to ascertain joint and bending geometry.
Basic principle: The inertial mapping system (PROBE) is an autonomous electromechanical device that through the triad of accelerometers and gyros, measures and records the down-line distance, angular changes, and accelerations of the PROBE and that through postprocessing, computes a high-resolution 3-D pipe centerline. GPS surveying is used to establish the start, intermediate, and end points of the mapping survey. Results are uploaded into any industry geographic information system (GIS) for further viewing, integration, and analysis.
Limitations: The PROBE system is limited as follows: (1) current battery/memory capacity is limited to 3 h of run time, and depending on pulling or flowing speed, this may be up to 3 km; (2) the calibrated accuracy is based on typical horizontal directional drilling (HDD)–installed pipe (long sweep radius, smooth pipe wall, constant operating temperature, and the ability to pull at consistent velocity); and (3) the pipe trajectory (short radius bends pose challenges for passage and degrade the position accuracy due to the heading sensitivity of the gyros).
Additional notes: Challenges lie in the ability to insert/extract these tools in a cost-effective, safe, and reliable manner. Development of a sound operations plan is required to manage the GPS survey, tool tracking, and site selection for intermediate points (or markers, similar to pigging aboveground markers, or AGMs) to keep the inertial errors to a minimal and acceptable level.

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Related SHRP 2 Research

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